

# What is the impact of 3D radiative effects on the global radiation budget?

Robin Hogan

ECMWF and the University of Reading

Contributions from

*Sophia Schäfer and Christine Chiu (University of Reading, UK)*

*Carolin Klinger and Bernhard Mayer (LMU, Germany)*

*Maike Ahlgrimm, Richard Forbes and Alessio Bozzo (ECMWF)*

# Overview

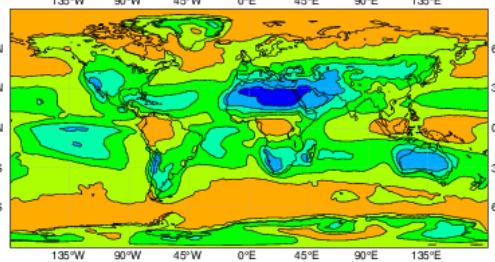
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- A puzzling bias
- Representing cloud structure in radiation schemes
- Conceptual models for 3D cloud-radiation effects
- The SPARTACUS solver
- How big is a cloud?
- An estimate of the global impact of 3D radiation

# ECMWF cycle 43R1: clouds in uncoupled model climate

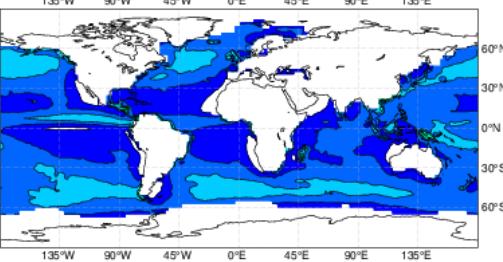
## Cloud cover: model

Total Cloud Cover gj1y Sep 2000 nmon=12 nens=4 Global Mean: 65 50N-S Mean: 61.1



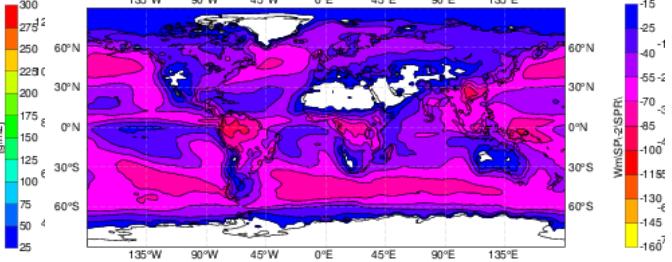
## LWP: model

Liquid Water Path gj1y Sep 2000 nmon=12 nens=4 Global Mean: 56.5



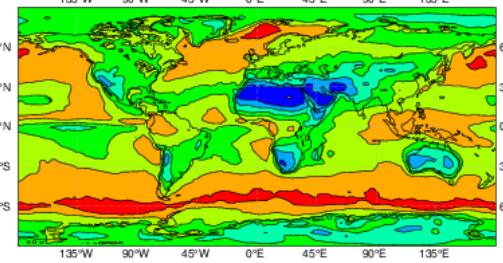
## SW CRE: model

TOA swcf gj1y Sep 2000 nmon=12 nens=4 Global Mean: -46.4 50S-50N Mean: -49.1



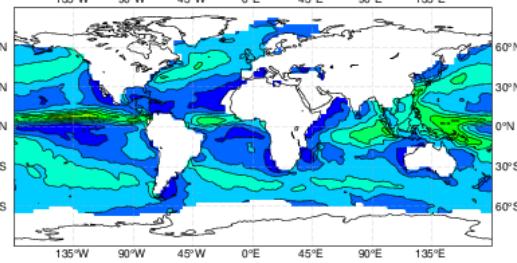
## Cloud cover: MODIS

Total Cloud Cover MODIS Sep 2000 nmon=12 50N-S Mean: 68.9



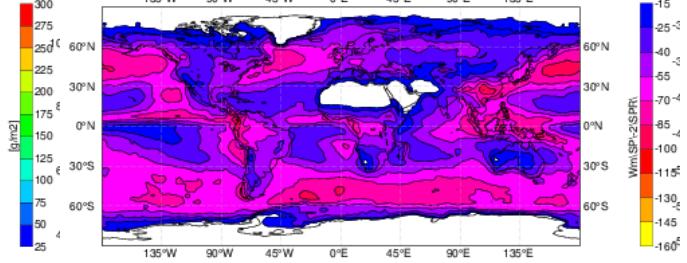
## LWP: SSMI

Liquid Water Path SSMI Wentz V6 Sep 2000 nmon=12 Global Mean: 84.2



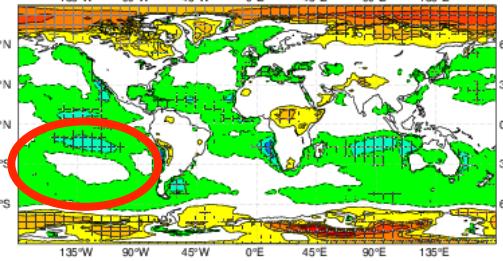
## SW CRE: CERES-EBAF

OA swcf CERES-EBAF Sep 2000 nmon=12 Global Mean: -47.2 50S-50N Mean: -49.3



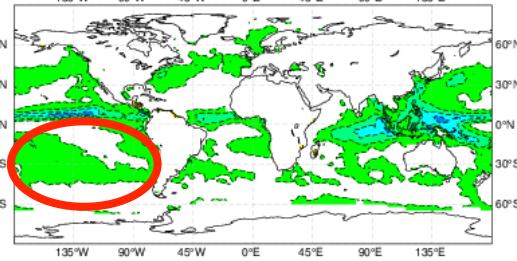
## Cloud cover: difference

Difference gj1y - MODIS 50N-S Mean err: -7.86 50N-S rms 11.8



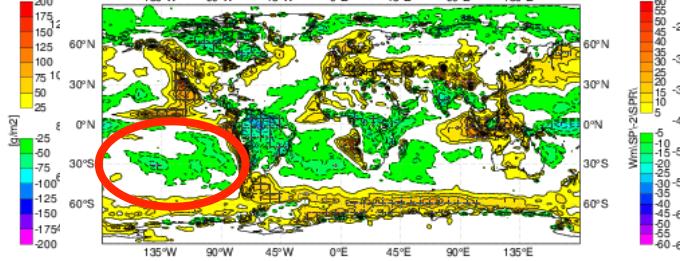
## LWP: difference

Difference gj1y - SSMI Wentz V6 Global Mean err: -27.7 RMS 34.9



## SW CRE: difference (mean 0.2 W m<sup>-2</sup>)

Difference gj1y - CERES-EBAF 50N-S Mean err 0.247 50N-S rms 9.95

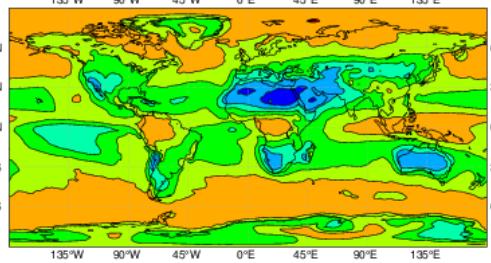


Cloud cover and LWP are too low, yet clouds are too reflective

# “Improvements”: less cloud overlap and less heterogeneity

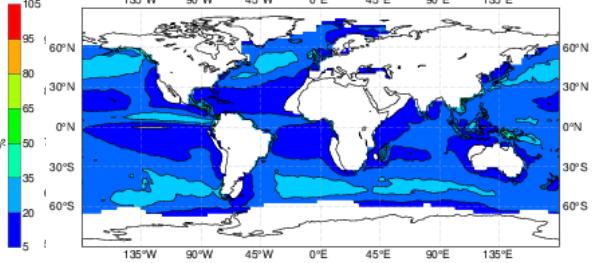
## Cloud cover: model

Total Cloud Cover gl6j Sep 2000 nmon=12 nens=4 Global Mean: 67 50N-S Mean: 63.5



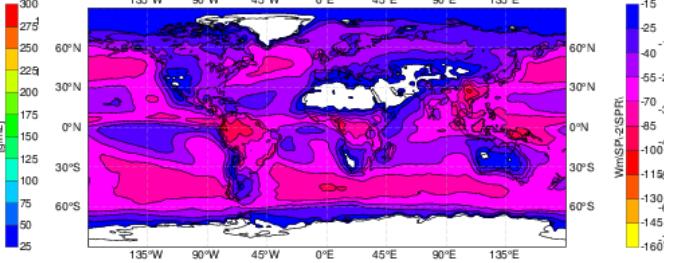
## LWP: model

Liquid Water Path gl6j Sep 2000 nmon=12 nens=4 Global Mean: 56.4



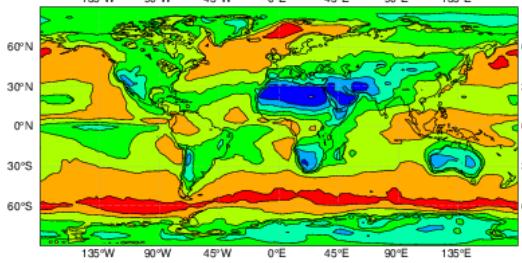
## SW CRE: model

TOA swcf gl6j Sep 2000 nmon=12 nens=4 Global Mean: -49.6 50S-50N Mean: -53



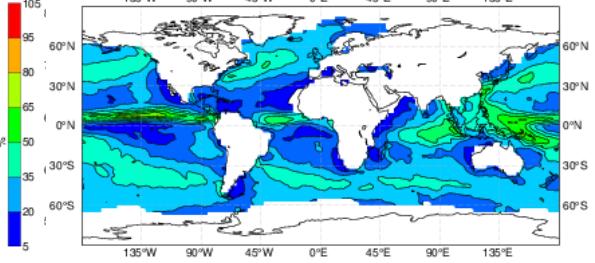
## Cloud cover: MODIS

Total Cloud Cover MODIS Sep 2000 nmon=12 50N-S Mean: 68.9



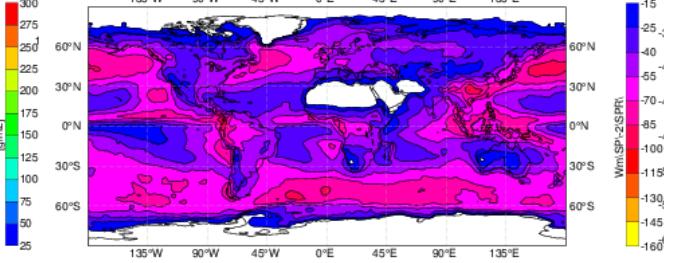
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Liquid Water Path SSMI Wentz V6 Sep 2000 nmon=12 Global Mean: 84.2



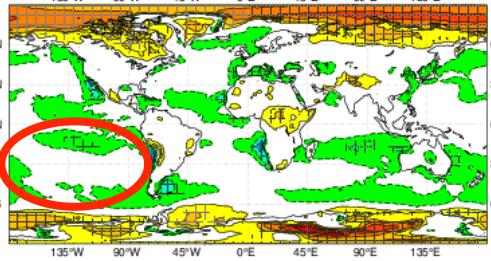
## SW CRE: CERES-EBAF

OA swcf CERES-EBAF Sep 2000 nmon=12 Global Mean: -47.2 50S-50N Mean: -49.3



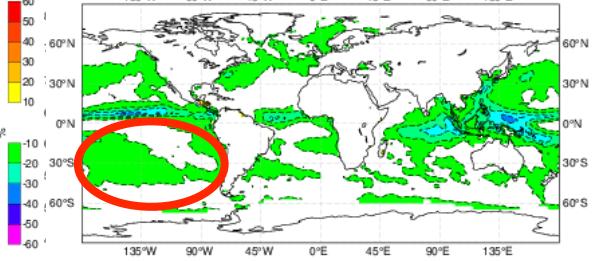
## Cloud cover: difference

Difference gl6j - MODIS 50N-S Mean err: -5.45 50N-S rms 9.58



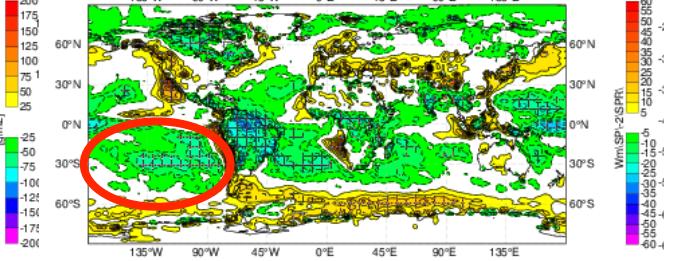
## LWP: difference

Difference gl6j - SSMI Wentz V6 Global Mean err: -27.9 RMS 34.7



## SW CRE: difference (mean -3.6 W m<sup>-2</sup>)

Difference gl6j - CERES-EBAF 50N-S Mean err: -3.63 50N-S rms 10.9



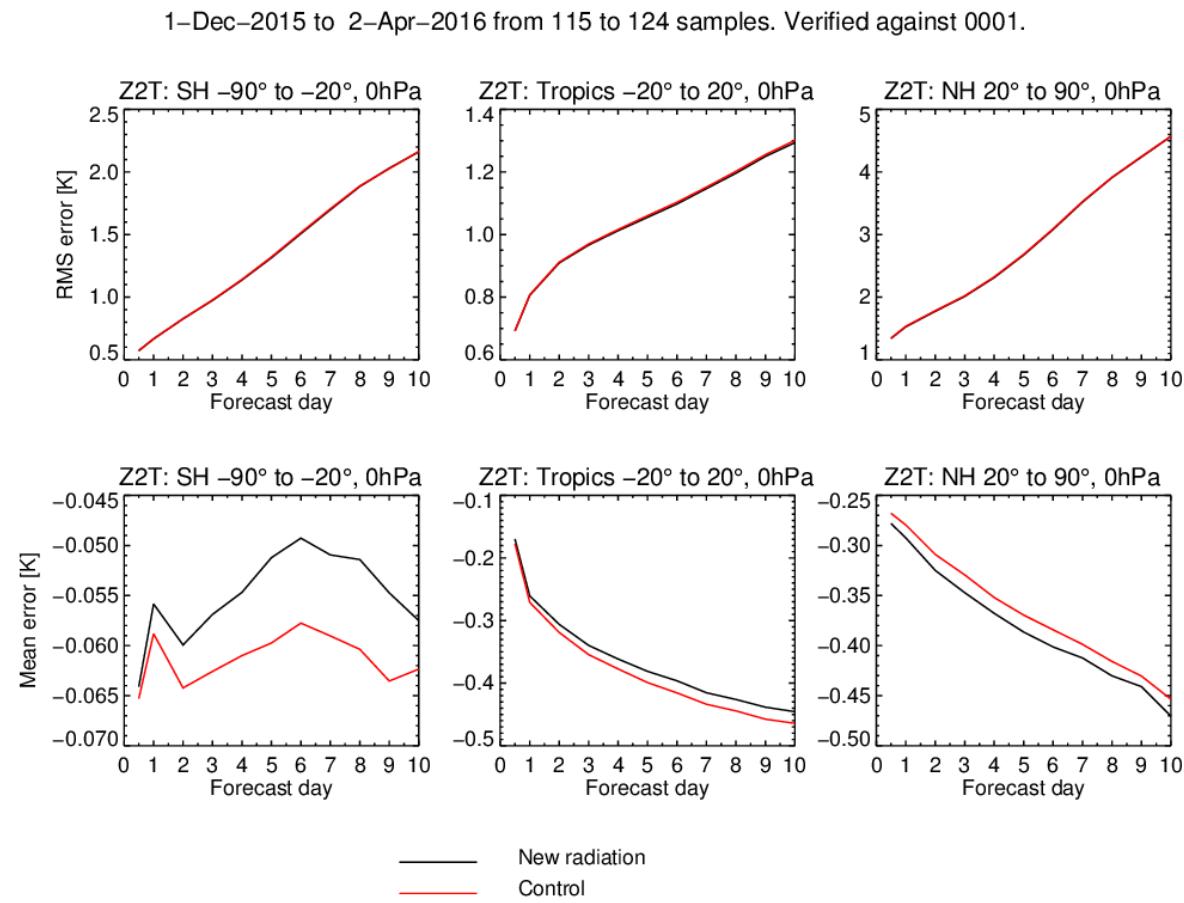
Cloud cover is better, SW CRE is worse

# 2-m temperature bias (winter example)

- **RMS errors** are one way to judge whether a new model version improves forecasts

- **Mean errors** are small but negative and grow during the forecast towards the climatic biases

- A related puzzle: global-mean shortwave cloud radiative effect is about right but temperatures are a little low

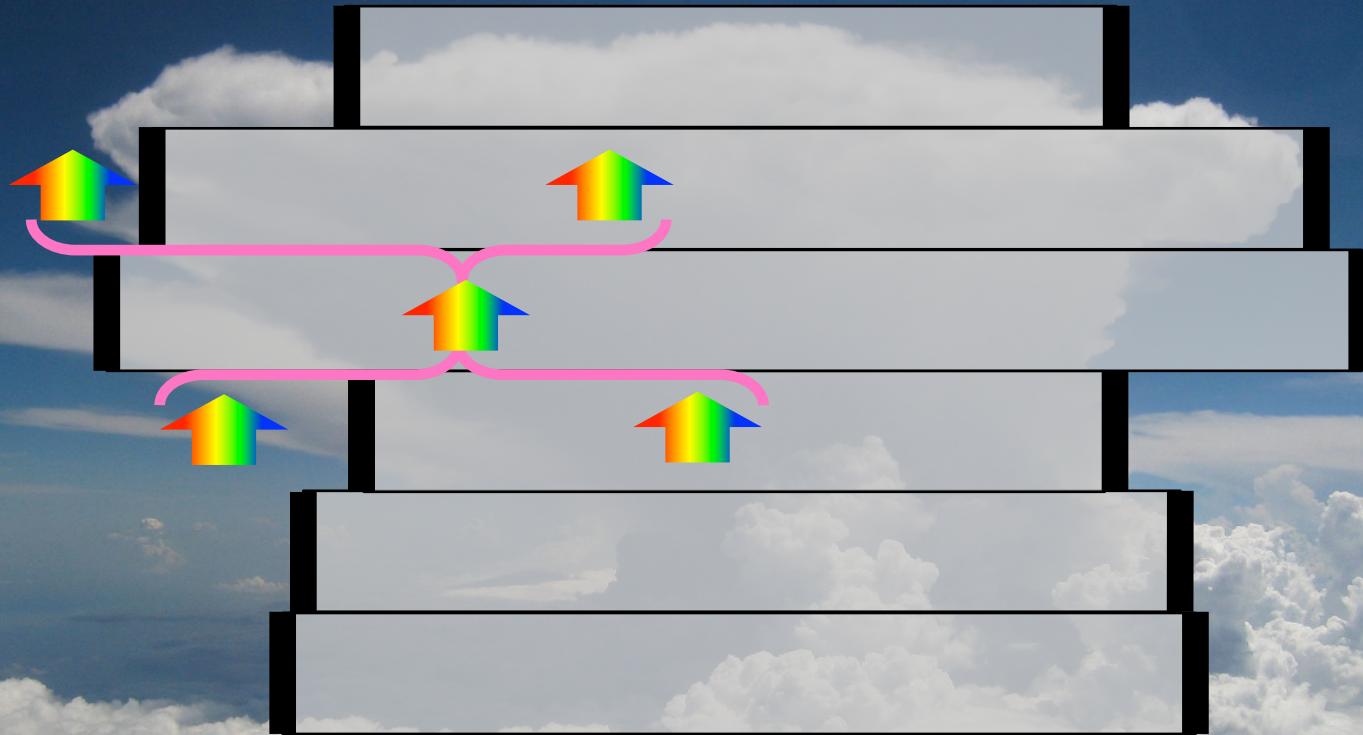


**How do we compute how this interacts with radiation?**



# Plane-parallel, maximum-random overlap

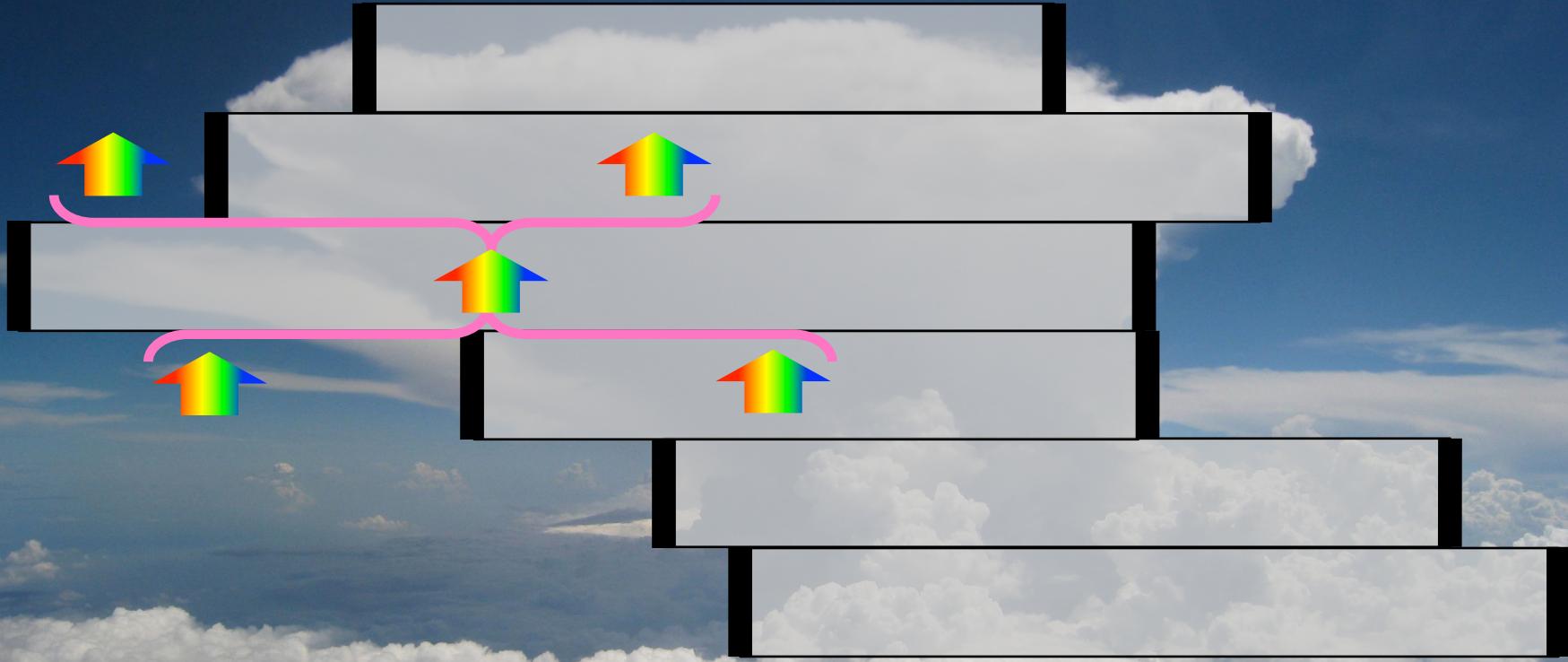
- Most models circa 2000



- *Model variables needed:* cloud fraction, water content
- Reflection & transmission computed for clear & cloudy regions separately
- Fluxes merged at layer interfaces according to cloud fraction

# Realistic overlap

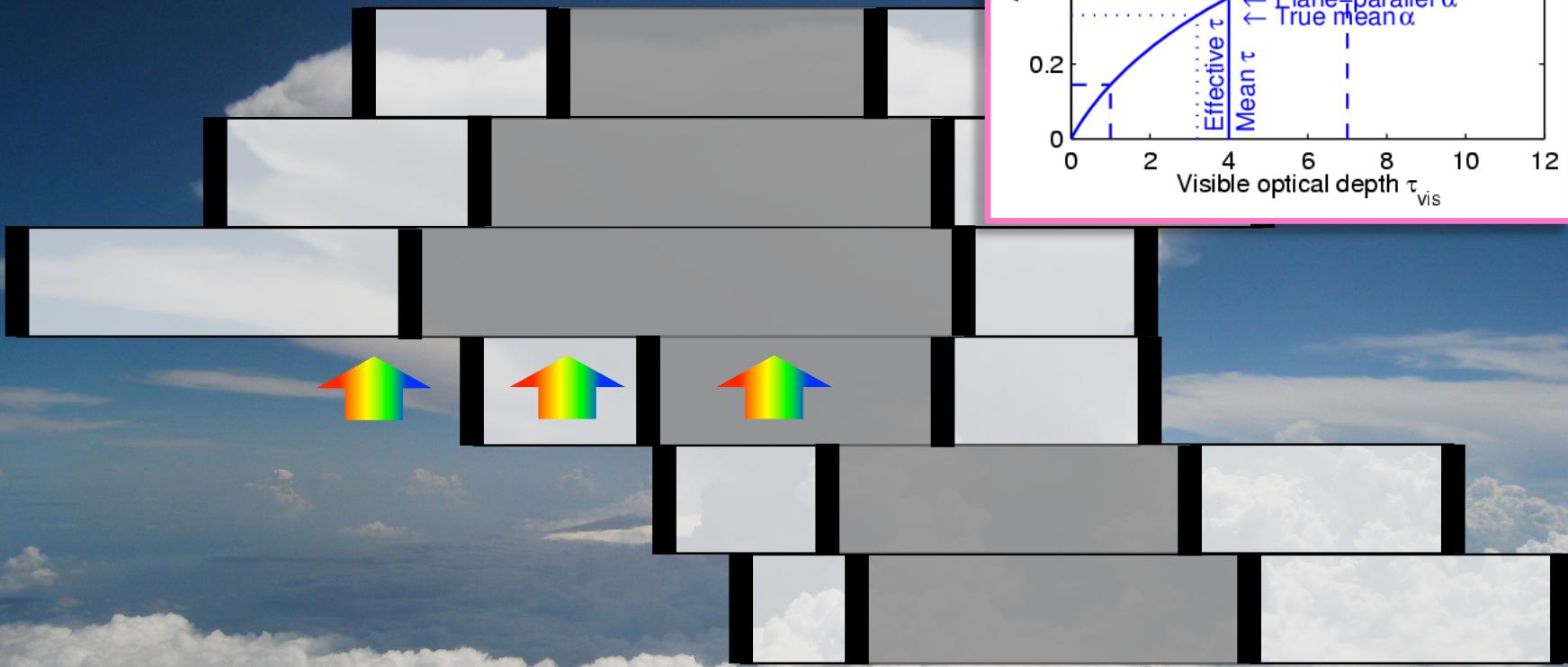
- Increases cloud cover and hence magnitude of cloud radiative effect
- Net impact  $-1.9 \text{ W m}^{-2}$  at surface and TOA (Shonk & Hogan 2010)



- *Extra input: overlap decorrelation length* from cloud radar  $\sim 2 \text{ km}$ 
  - Ground-based (Hogan & Illingworth 2000, Mace & Benson-Troth 2002)
  - CloudSat (Barker 2008, Shonk et al. 2010)

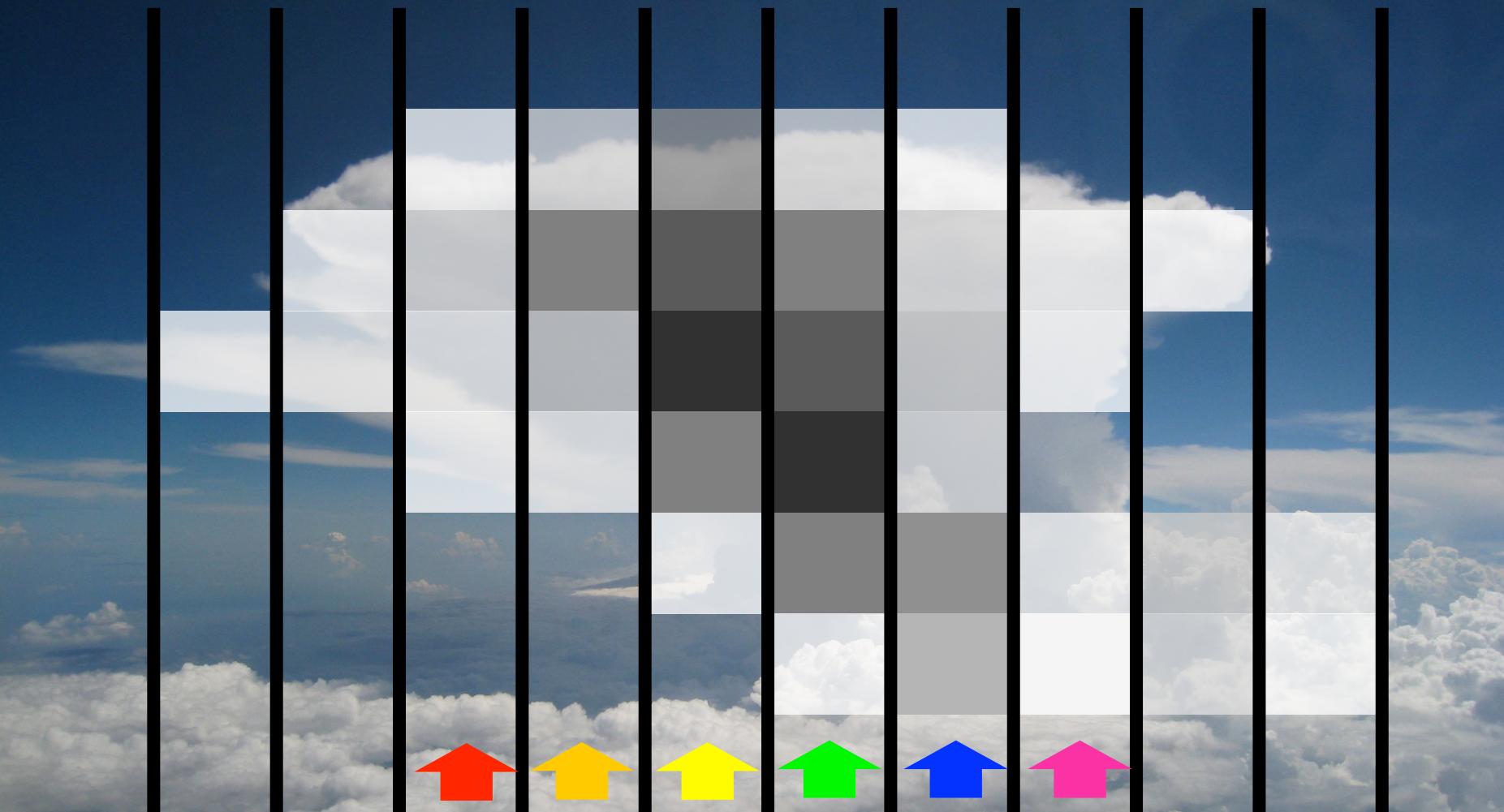
# Tripleclouds (Shonk & Hogan 2008)

- Cloud structure *reduces* cloud reflectance
- Net impact  $4.1 \text{ W m}^{-2}$  (TOA),  $3.8 \text{ W m}^{-2}$  (surf)



- Cloud water fractional standard deviation  $\sim 0.75$ 
  - Satellite & cloud radar (Barker, Shonk, Cahalan, Oreopoulos, Rossow...)
- Cloud water overlap decorrelation length  $\sim 1 \text{ km}$ 
  - Ground-based cloud radar (e.g. Hogan & Illingworth 2003)

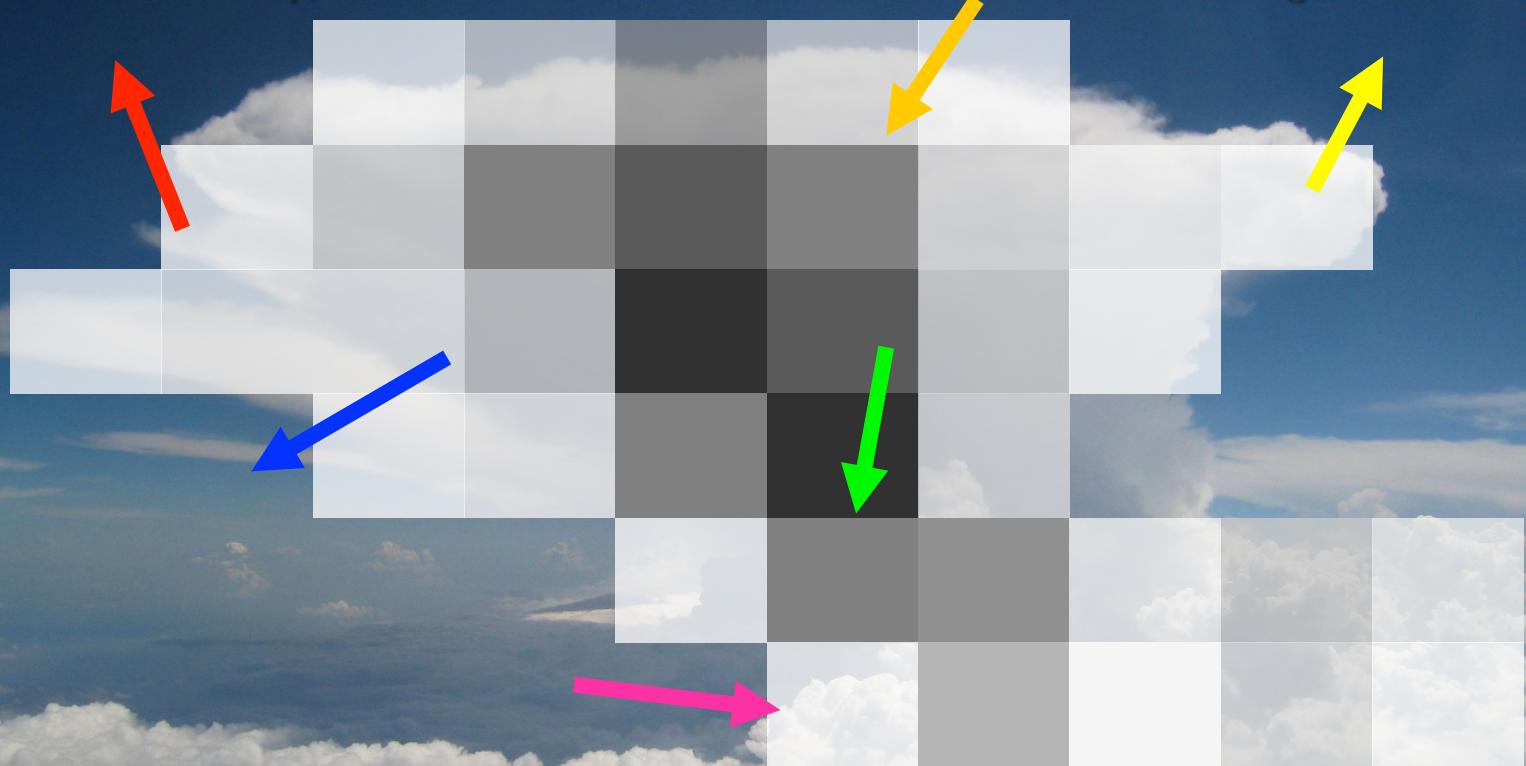
## Monte-Carlo Independent Column Approximation (McICA) – Pincus et al. (2005)



- Info required similar to Tripleclouds but computationally faster
- Use of stochastic cloud generator leads to some noise in fluxes
- Now used in many (most?) global weather and climate models

# Full Monte Carlo (being investigated by Barker et al.)

- “It’s better to solve the right problem approximately than the wrong problem exactly,” or “random errors are better than biases.” (for climate!)



- Use 3D cloud distribution generated by a stochastic model in each gridbox
- How many light rays are needed for random errors to be tolerable? 500?
  - NWP models tolerate random errors much less than climate models
- Monte Carlo at least provides good benchmark for approximate schemes

# Mechanisms for shortwave 3D effects

## • Side illumination

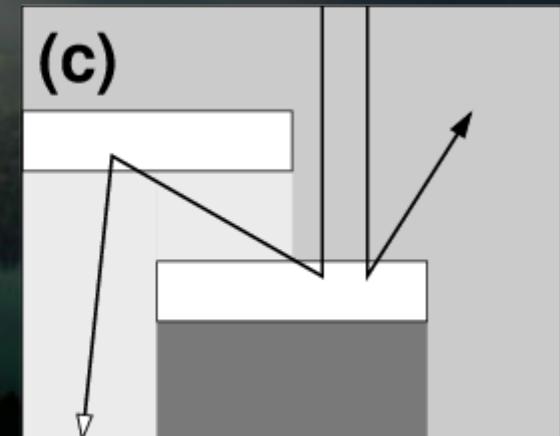
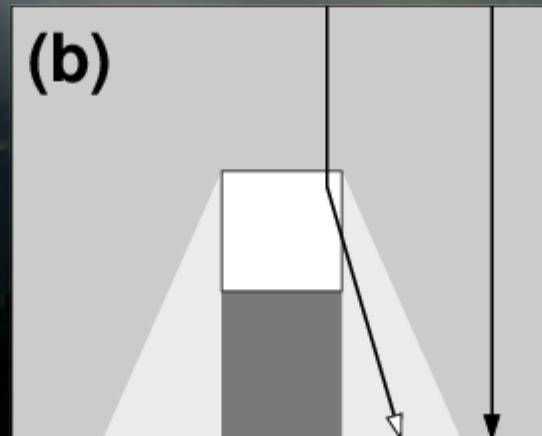
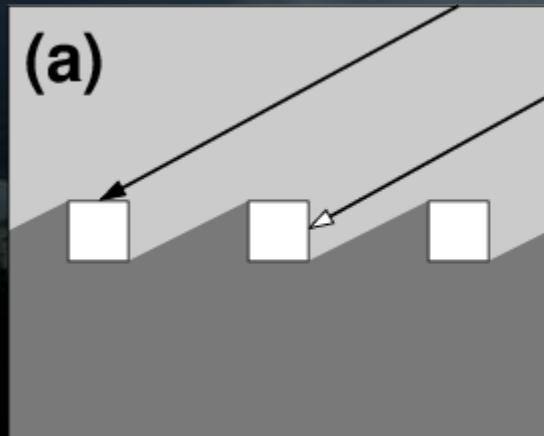
- Strongest when sun near horizon
- Increases chance of sunlight intercepting cloud

## • Side escape

- Strongest for overhead sun
- Forward scattering leads to more sunlight penetration
- Second-order importance

## • In-region transport

- Systematically reduces reflectance for all solar zenith angles



# Idealized calculation: what is the albedo of this scene?

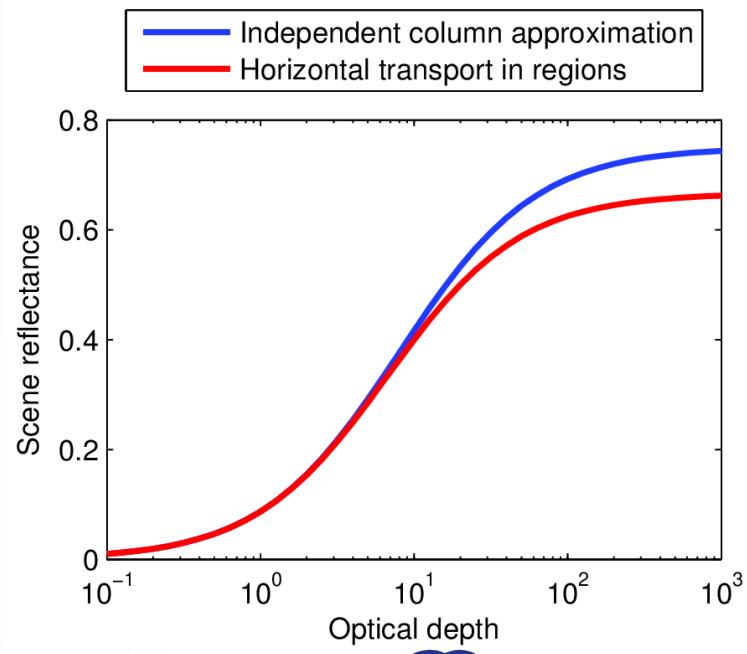
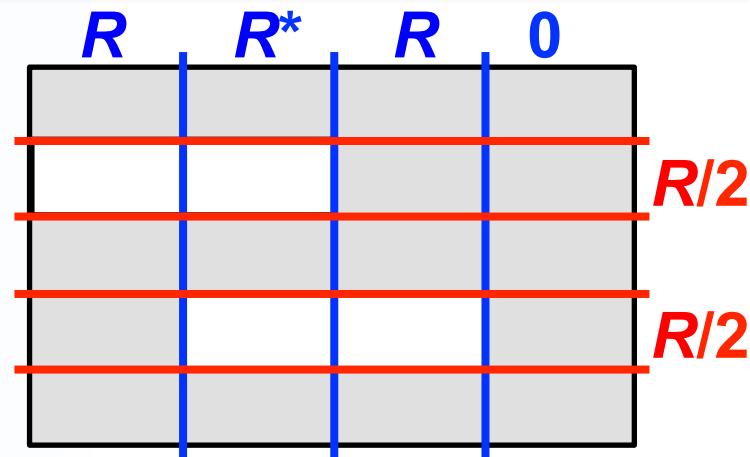
- Surface albedo = 0
- Reflectance of each cloud:  $R$
- No absorption so transmittance  $T = 1 - R$

## Independent column approximation

- Reflectance of 2 non-absorbing clouds
  - Adding method with  $R^* = 2R/(1+R)$
- Reflectance of scene
- Weighted average  $R_{\text{scene}} = R/2 + R^*/4 = R(1+R/2)/(1+R)$
- Optically thick limit:  $R_{\text{scene}} = 3/4$

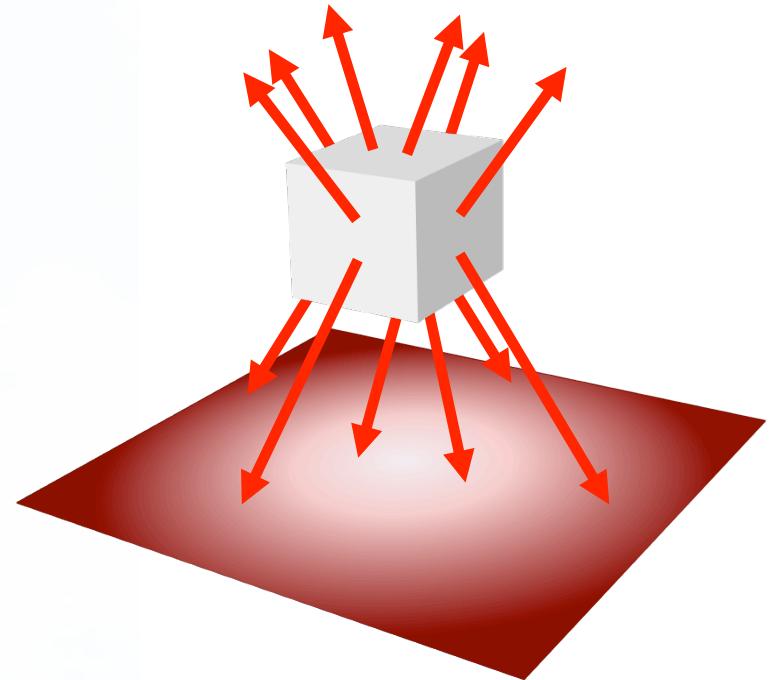
## Horizontal transport in regions

- Mean reflectance of layer =  $R/2$
- Reflectance of scene
  - Random overlap so apply adding method to mean reflectances:  $R_{\text{scene}} = 2(R/2)/(1+R/2) = 2R/(2+R)$
- Optically thick limit:  $R_{\text{scene}} = 2/3$



# Conceptual model for longwave 3D effects

- Radiation can now be emitted from the side of a cloud, increasing downwelling at the surface
- A useful benchmark: *for an isolated, optically thick, cubic cloud in vacuum, 3D effects increase downwelling flux at the surface by a factor of 3*



- Clouds are not cubes, the atmosphere is not a vacuum to longwave radiation: many radiation people assume 3D effects are negligible in the longwave... *are they right?*

# SPARTACUS “Speedy Algorithm for Radiative Transfer through Cloud Sides”

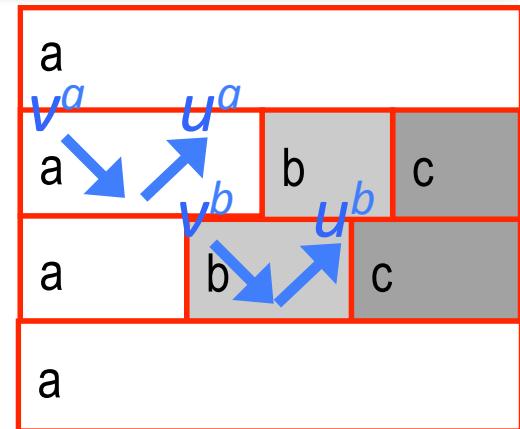
- Starting point: “Tripleclouds” method
  - Represent cloud heterogeneity via three regions at each height
- Extra terms added to two-stream equations:

$$dv \uparrow a / dz = \beta \downarrow e (-\gamma \downarrow 1 \uparrow a v \uparrow a + \gamma \downarrow 2 \uparrow a v \uparrow b) - f \uparrow ab v \uparrow a + f \uparrow ba v \uparrow b$$

$$-du \uparrow a / dz = \beta \downarrow e (-\gamma \downarrow 1 \uparrow a u \uparrow a + \gamma \downarrow 2 \uparrow a v \uparrow a + s \uparrow a + ) - f \uparrow ab u \uparrow a + f \uparrow ba u \uparrow b$$

- $f_{ab} = L_{ab} / 2ca$  Length of cloud perimeter per unit gridbox area
- Assuming clouds are *randomly distributed*, we obtain:

Fraction of gridbox occupied by clear skies (region a)



New terms representing exchange between regions

# Matrix solution in a single layer (shortwave)

- Define diffuse upwelling, diffuse downwelling and direct downwelling as vectors  $\mathbf{u}$ ,  $\mathbf{v}$  and  $\mathbf{s}$ :

$$\mathbf{u} = \begin{pmatrix} u^a \\ u^b \\ \vdots \end{pmatrix}$$

- Write two-stream equations as:

$$\gamma_1 - \frac{d}{dz} \begin{pmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{s} \end{pmatrix} = \boldsymbol{\Gamma} \begin{pmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{s} \end{pmatrix}$$

where 9x9 matrix is composed of known terms analogous to the standard two-

$$\boldsymbol{\Gamma} = \begin{pmatrix} -\Gamma_1 & -\Gamma_2 & -\Gamma_3 \\ \Gamma_2 & \Gamma_1 & \Gamma_4 \\ & & \Gamma_0 \end{pmatrix}$$

- Solve

$$\begin{pmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{s} \end{pmatrix}_{z=z_1} = \exp(\boldsymbol{\Gamma} z_1) \begin{pmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{s} \end{pmatrix}_{z=0}$$

Matrix exponential

- Waterman (1981), Flatau & Stephens (1998)
- Can compute using Padé approximant plus scaling & squaring method (Higham 2005)

# Reflection and transmission matrices

- We want relationships between fluxes of the form:

$$\mathbf{u}(0) = \mathbf{T}\mathbf{u}(z_1) + \mathbf{R}\mathbf{v}(0) + \mathbf{S}^+ \mathbf{s}(0)$$

- Transmission matrix for 2 regions given by:

$$\mathbf{T} = \begin{pmatrix} T^{aa} & T^{ba} \\ T^{ab} & T^{bb} \end{pmatrix}$$

and likewise for  $\mathbf{R}$  and  $\mathbf{S}^\pm$

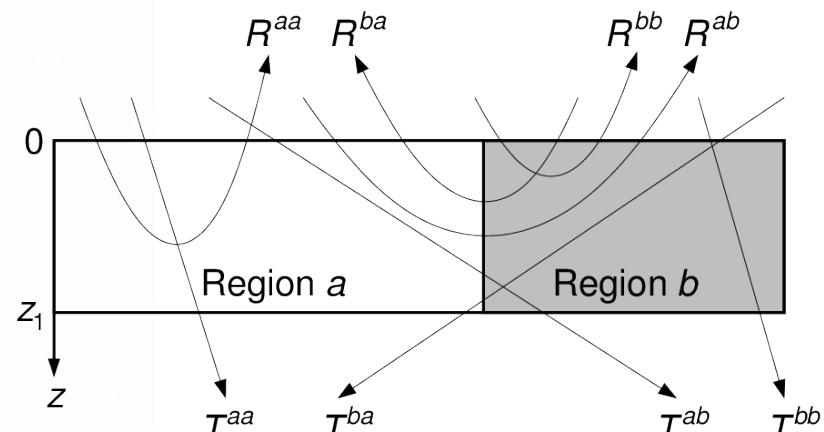
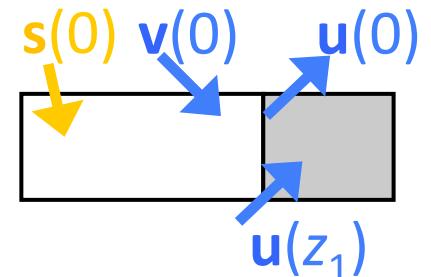
- If matrix exponential is decomposed as:

$$\exp(\Gamma z_1) = \begin{pmatrix} \mathbf{E}_{uu} & \mathbf{E}_{uv} & \mathbf{E}_{us} \\ \mathbf{E}_{vu} & \mathbf{E}_{vv} & \mathbf{E}_{vs} \\ \mathbf{E}_0 & & \end{pmatrix}$$

then reflection and transmission matrices given by:

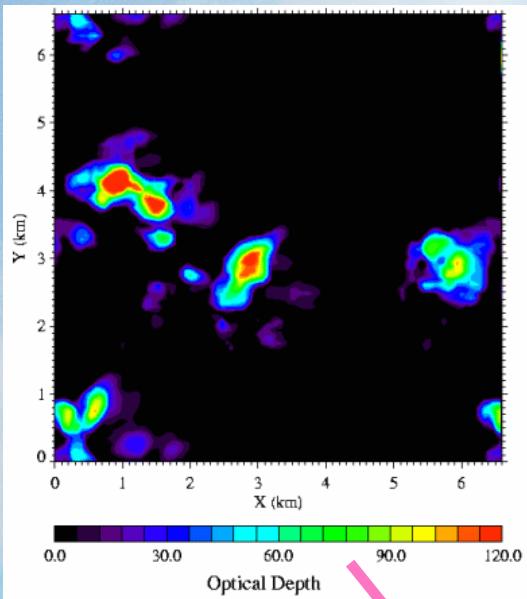
$$\mathbf{R} = -\mathbf{E}_{uu}^{-1} \mathbf{E}_{uv} \quad \mathbf{T} = \mathbf{E}_{vu} \mathbf{R} + \mathbf{E}_{vv}$$

- For scalars, get same answer as traditional Meador & Weaver (1980) formulas
- For speed, only use matrix exponential for partially cloudy layers

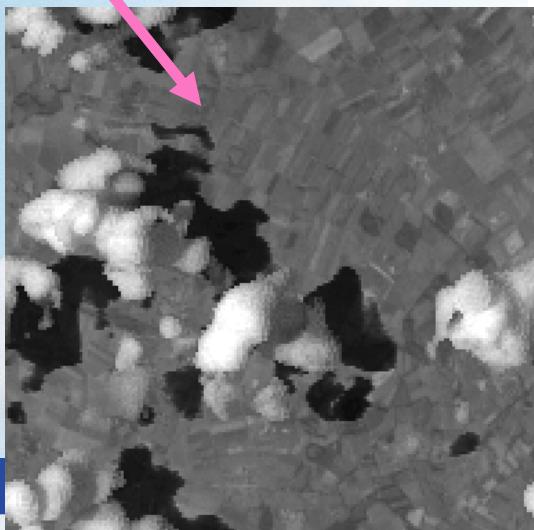


# Test with I3RC cumulus cloud

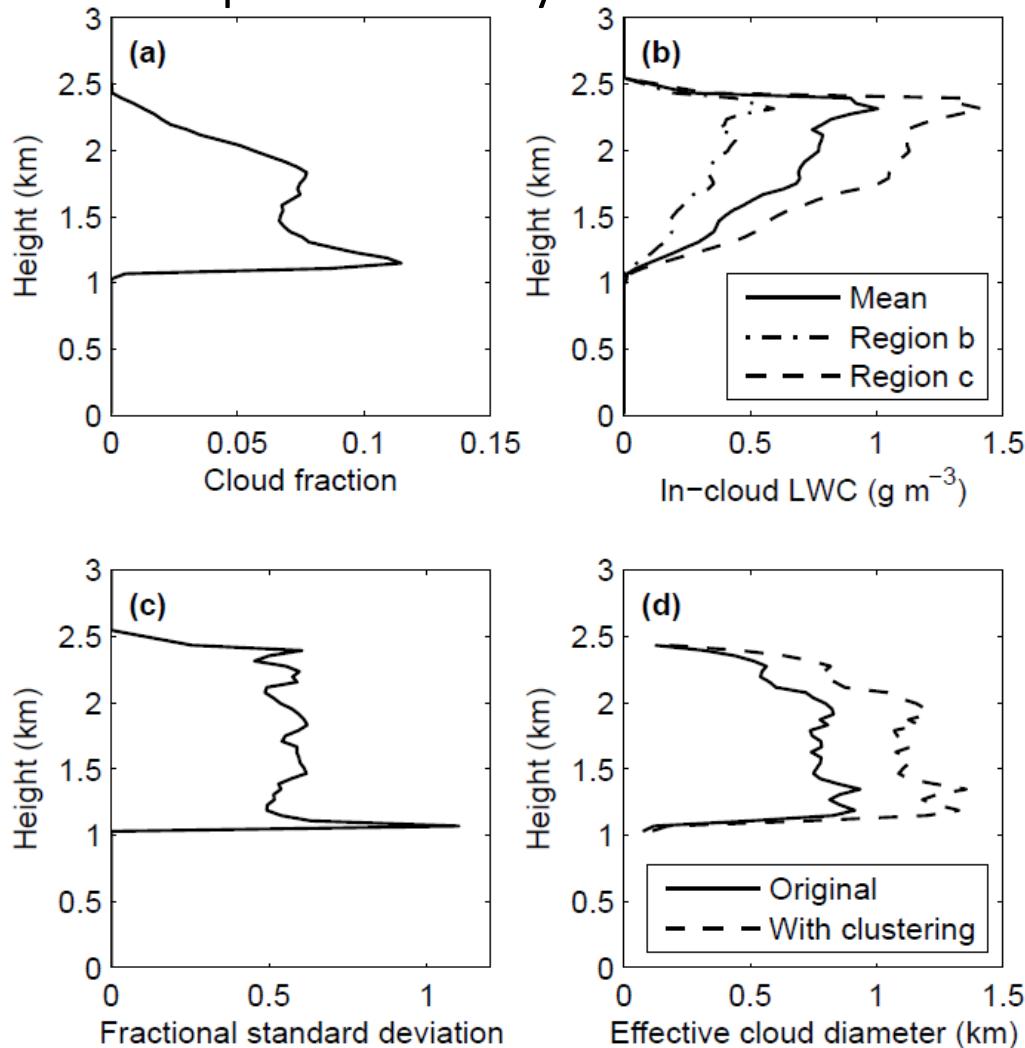
- Fully 3D simulations with MYSTIC



Thanks to Carolin  
Klinger &  
Bernhard Mayer,  
LMU Munich

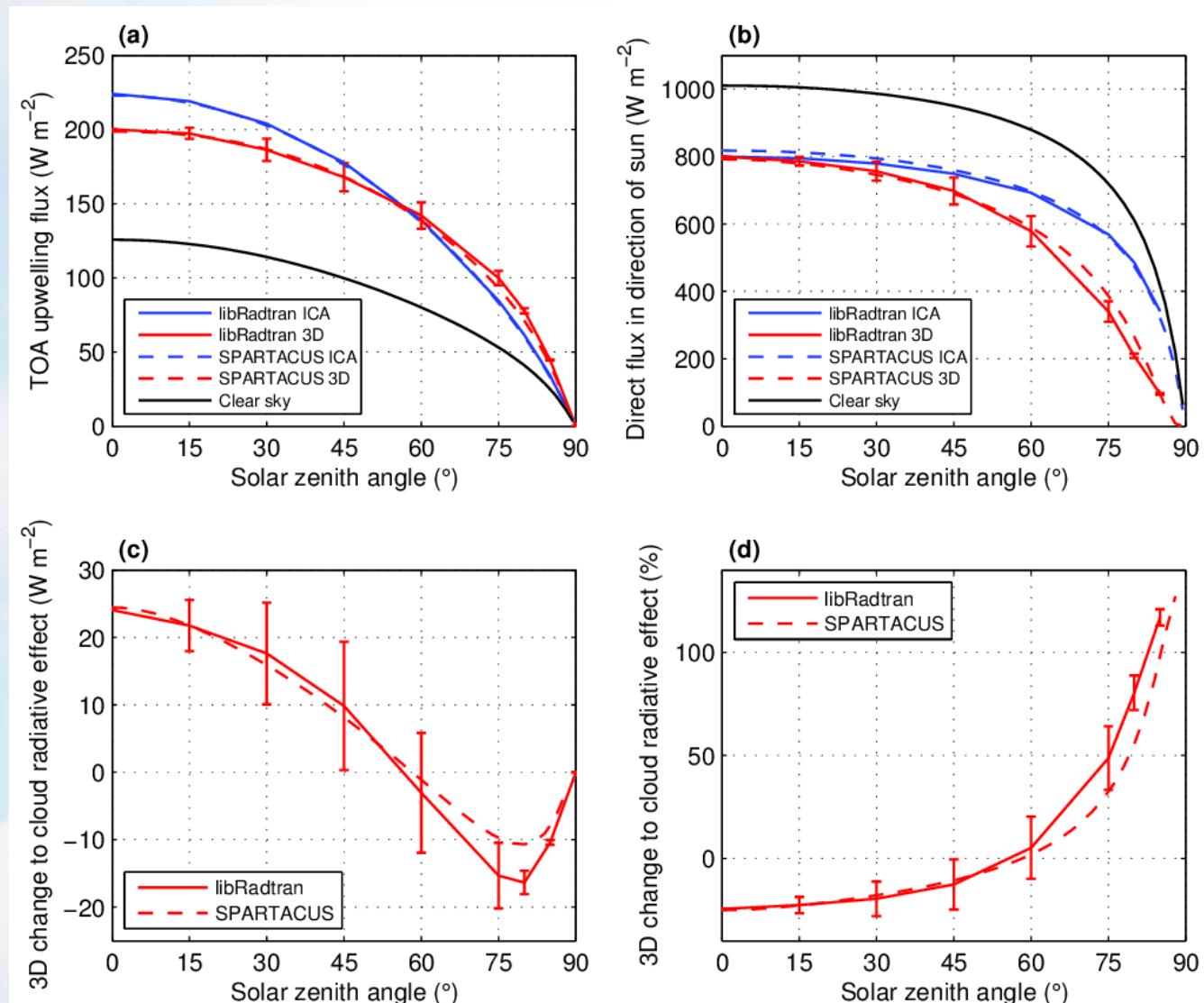


- Inputs needed by SPARTACUS



# Broadband shortwave SPARTACUS vs MYSTIC (Monte Carlo)

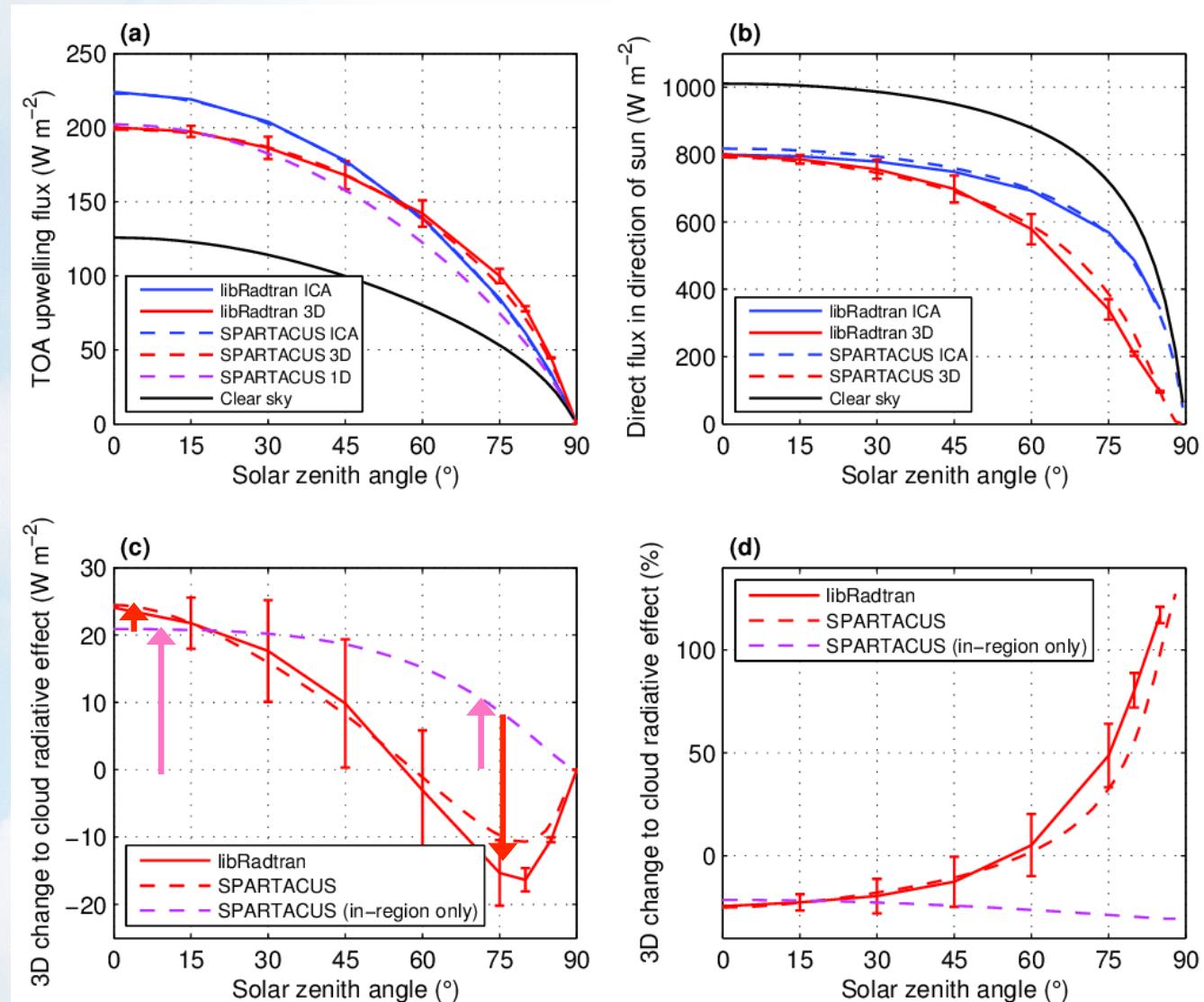
- Good match!
- Big difference in direct surface flux when sun low in the sky



Hogan et al. (JGR 2016)

# Broadband shortwave SPARTACUS vs MYSTIC (Monte Carlo)

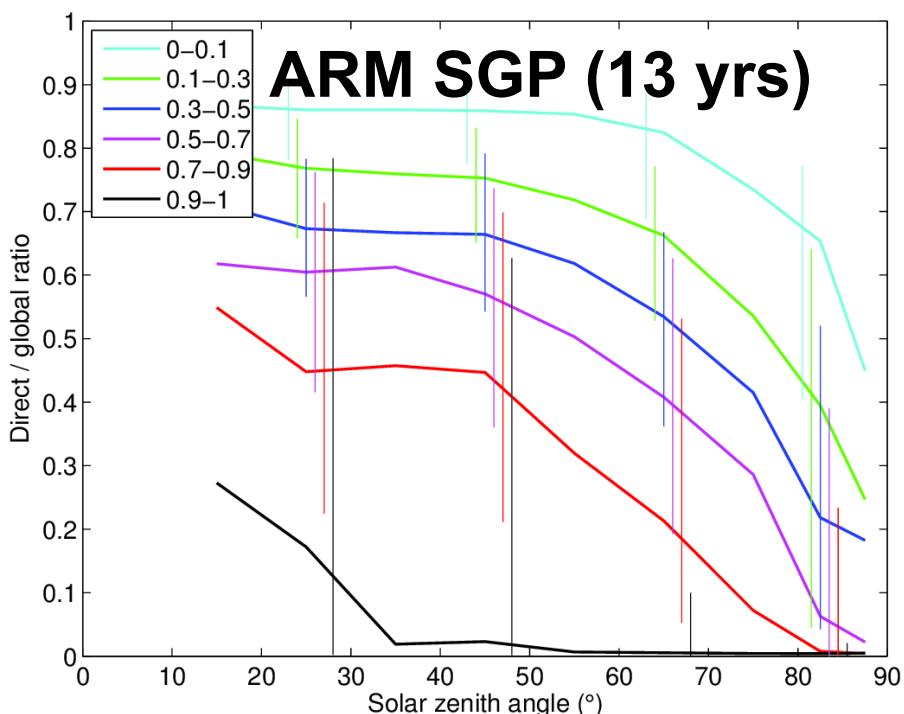
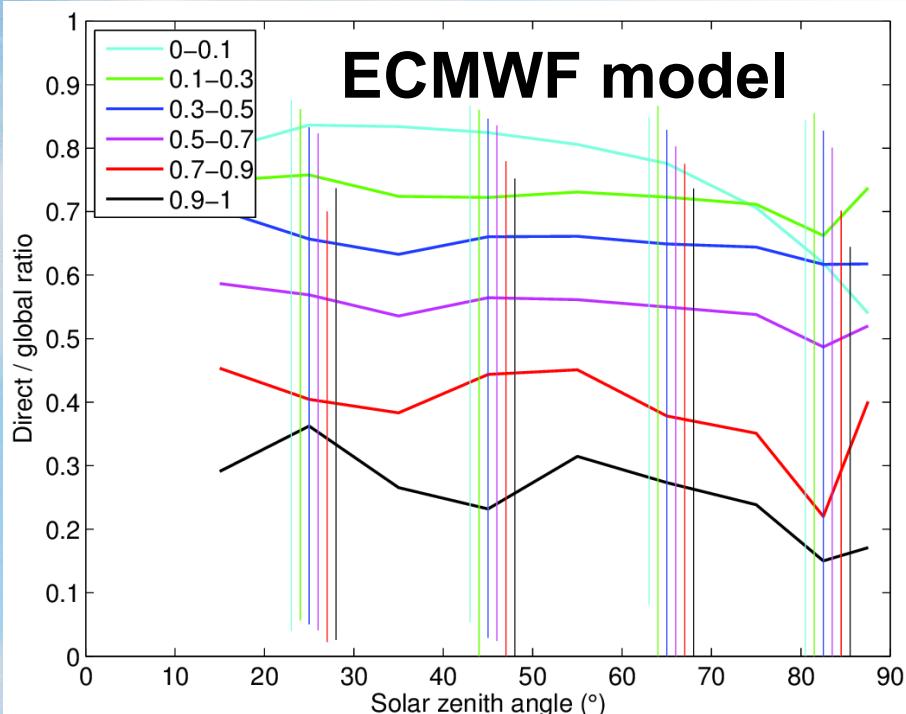
- Good match!
- Big difference in direct surface flux when sun low in the sky
- Change due to in-region horizontal transport
- Change due to cloud edge effects



Hogan et al. (JGR 2016)

# 3D effects in observations of direct/total downwelling flux

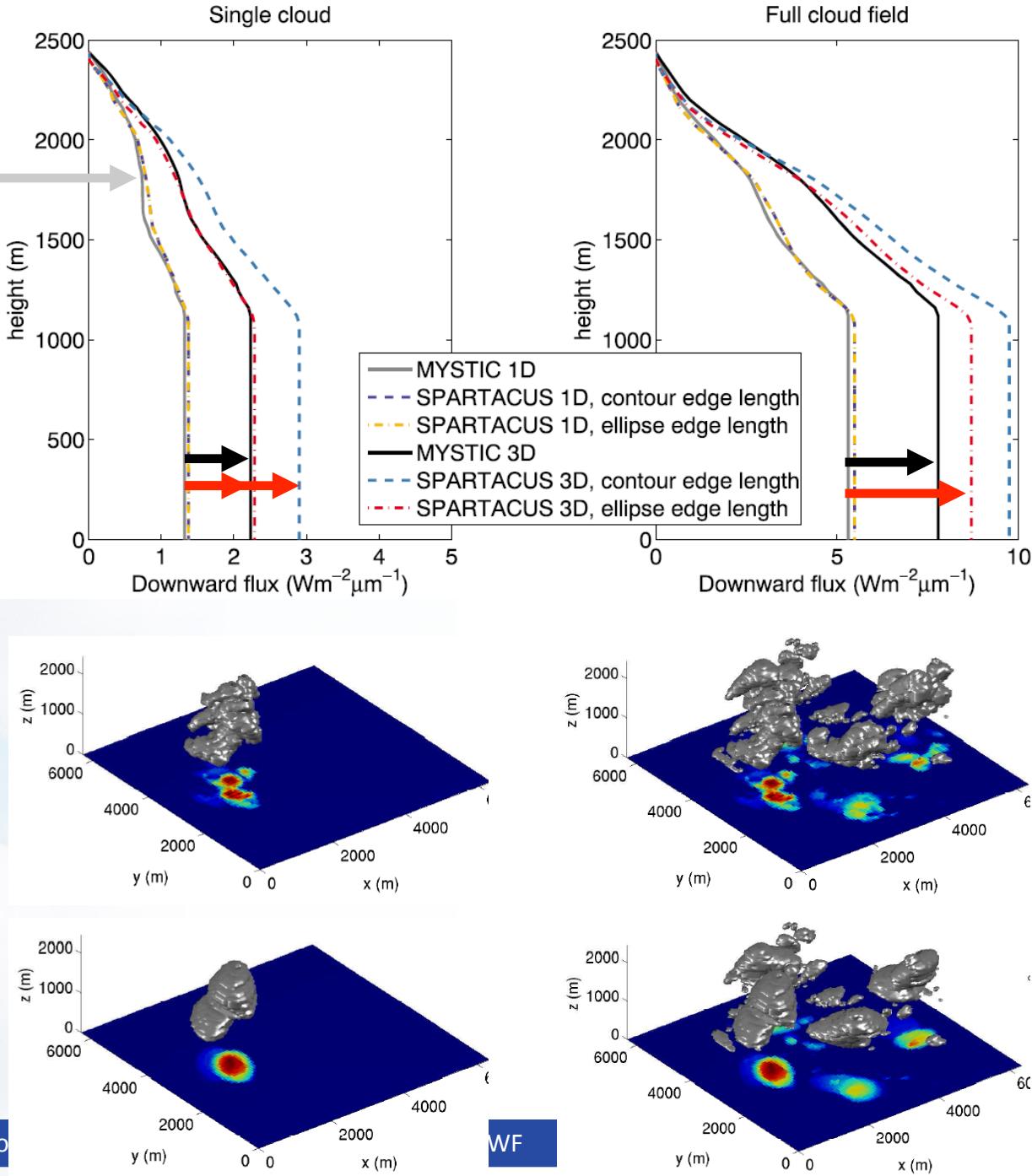
- Troccoli & Morcrette (2014) reported biases in ECMWF direct solar radiation from, important for solar energy industry
- Bin observations and model by solar zenith angle and cloud fraction, considering only cases of boundary-layer clouds (thanks to Maike Ahlgrimm):



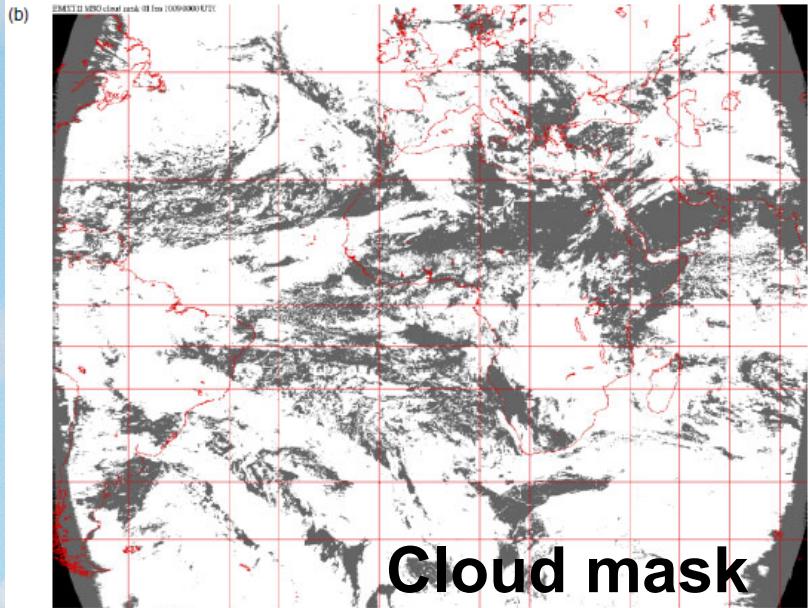
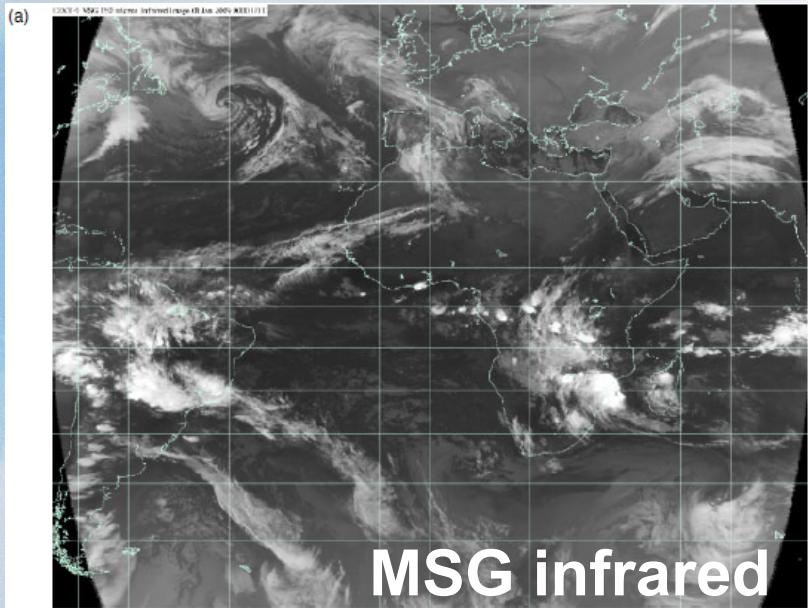
- Next step: apply new 3D radiation scheme to the ECMWF cloud fields to verify that differences are due to 3D effects

# Longwave...

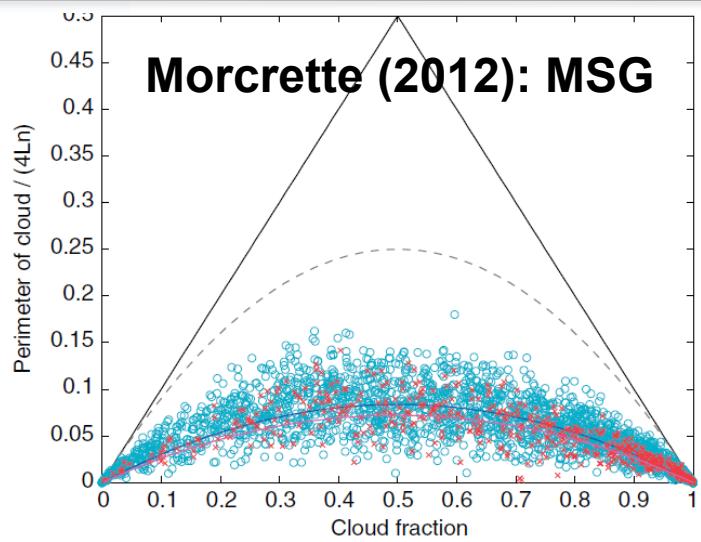
- Good 1D agreement
- MYSTIC 3D effect: 30% (the same in broadband)
- Too big in SPARTACUS?
- Use *radiatively effective cloud edge length*: contour of a fitted ellipse
- Consider full cloud field
- Effective edge length not sufficient: *clustering* is also important
- We know how to estimate the radiatively relevant edge length; clustering can only be represented approximately (multiply by 0.7 in this case)



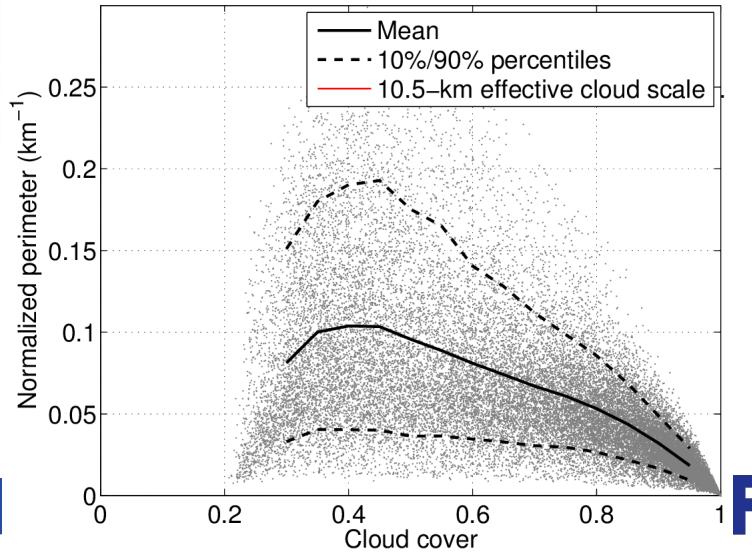
# How can we characterize cloud edge length in a model?



2016



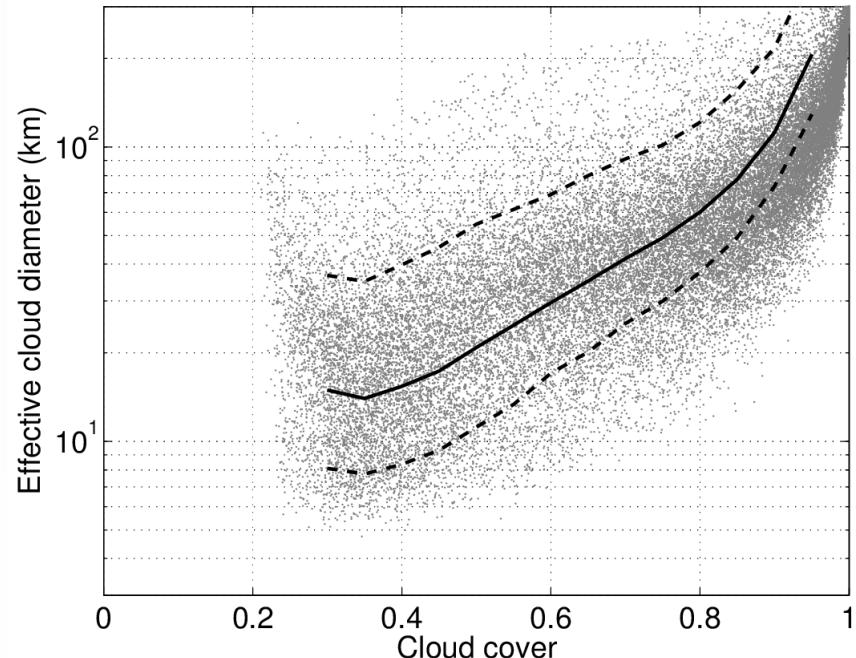
Jensen et al. (2006) data:  
MODIS stratocumulus



F

# Characterizing cloud perimeter vs. cloud fraction

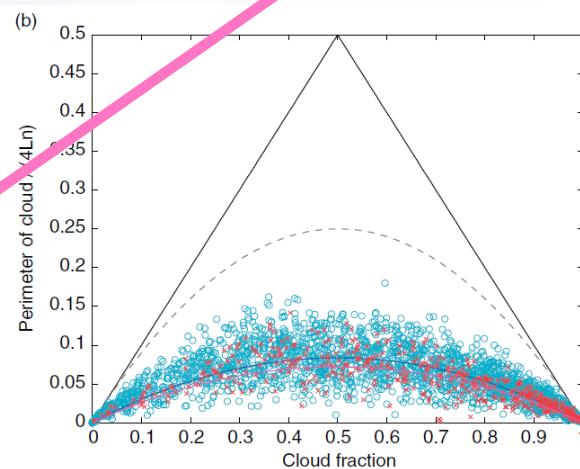
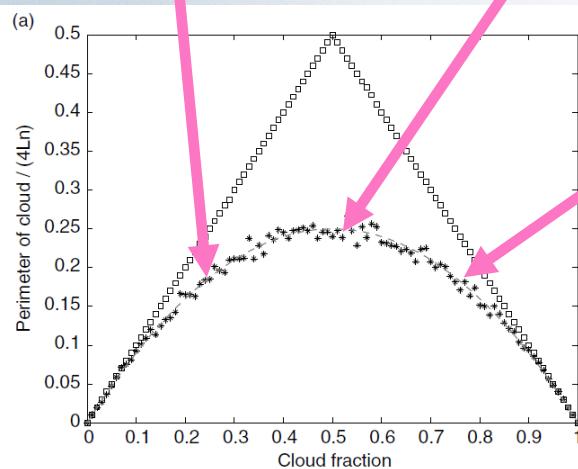
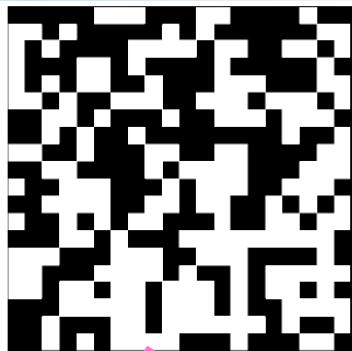
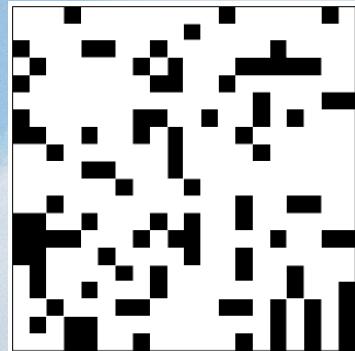
- Jensen et al. (2006) proposed *effective cloud diameter*  $D$ : diameter of identical circular clouds that have the same perimeter and area as the actual cloud field
  - If cloud area  $A = \pi(D/2)^2$  and perimeter  $P = \pi D$  then
  - Effective cloud diameter  $D = 4A/P = 4 \times \text{cloud cover} / \text{normalized perimeter}$
- Problem with this concept is that effective cloud diameter computed from real cloud fields is strongly dependent on cloud cover
- We seek an *effective cloud scale*  $S$  that is independent of cloud cover, and can be parameterized in GCMs



Jensen et al. (2006) data:  
MODIS stratocumulus

# Morcrette (2012)

- Conceptual model: fill a checkerboard randomly with squares of size  $S$ :



**Simulations**

**MSG data**

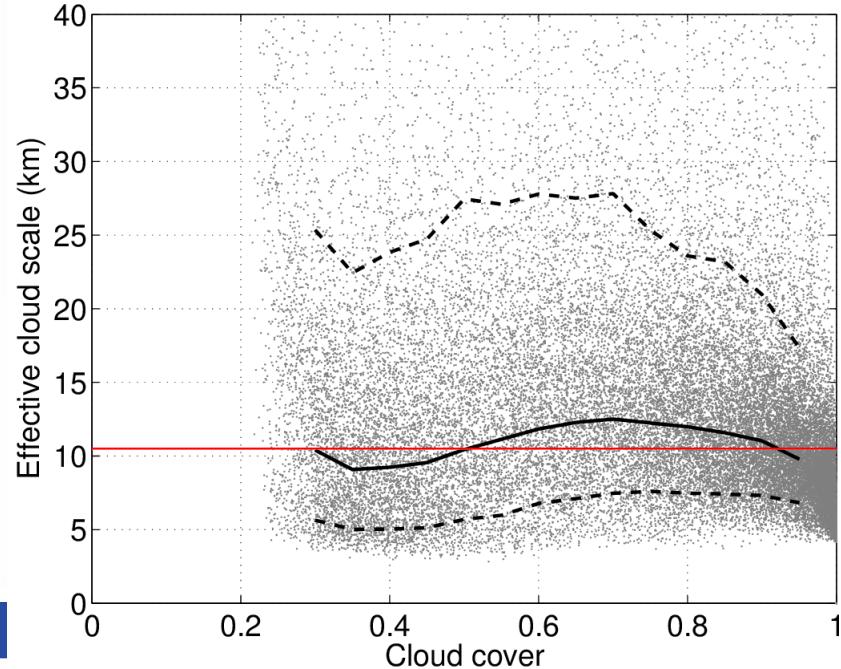
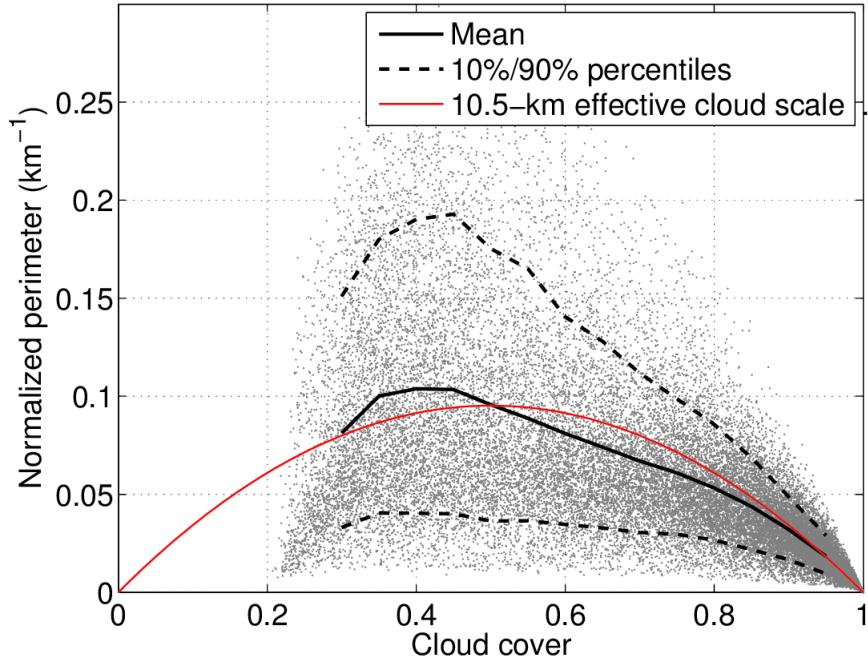
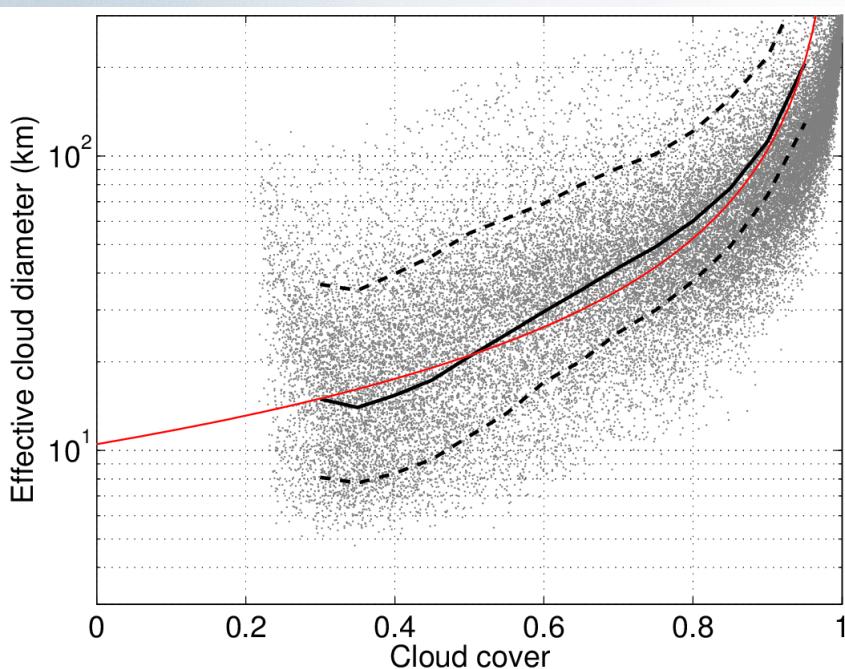
- Morcrette (2012) found that perimeter simulated in this way behaves the same as in observations:

$$P = 4A(1-A)/S$$

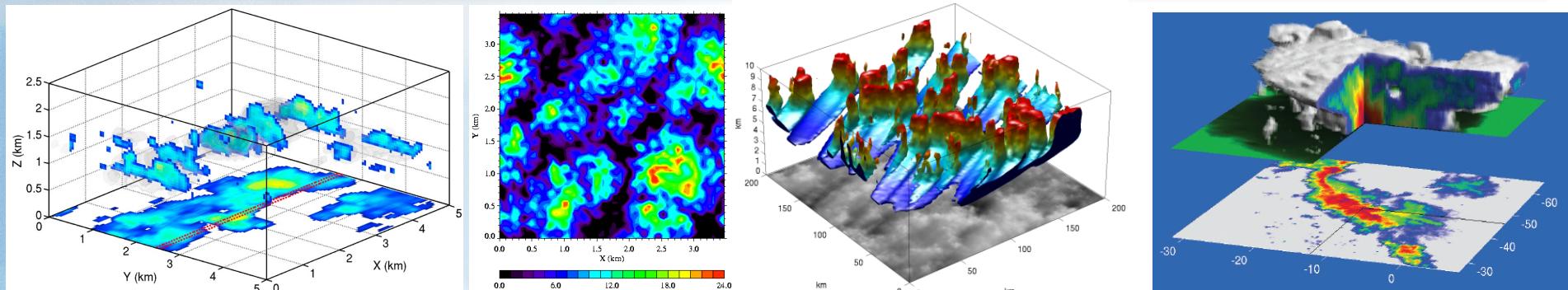
- His MSG data for all clouds yields  $S$  of around 10 km

# Apply concept to MODIS data

- 1-km MODIS is higher resolution than MSG
- Application to Jensen et al. stratocumulus data suggests effective cloud scale of around 10 km



# Estimates of effective cloud scale (Schäfer 2016, PhD thesis)



Cu: Fielding et al. (2014)

Sc: I3RC

Ci: Hogan & Kew (2005)

Cb: Stein et al. (2015)

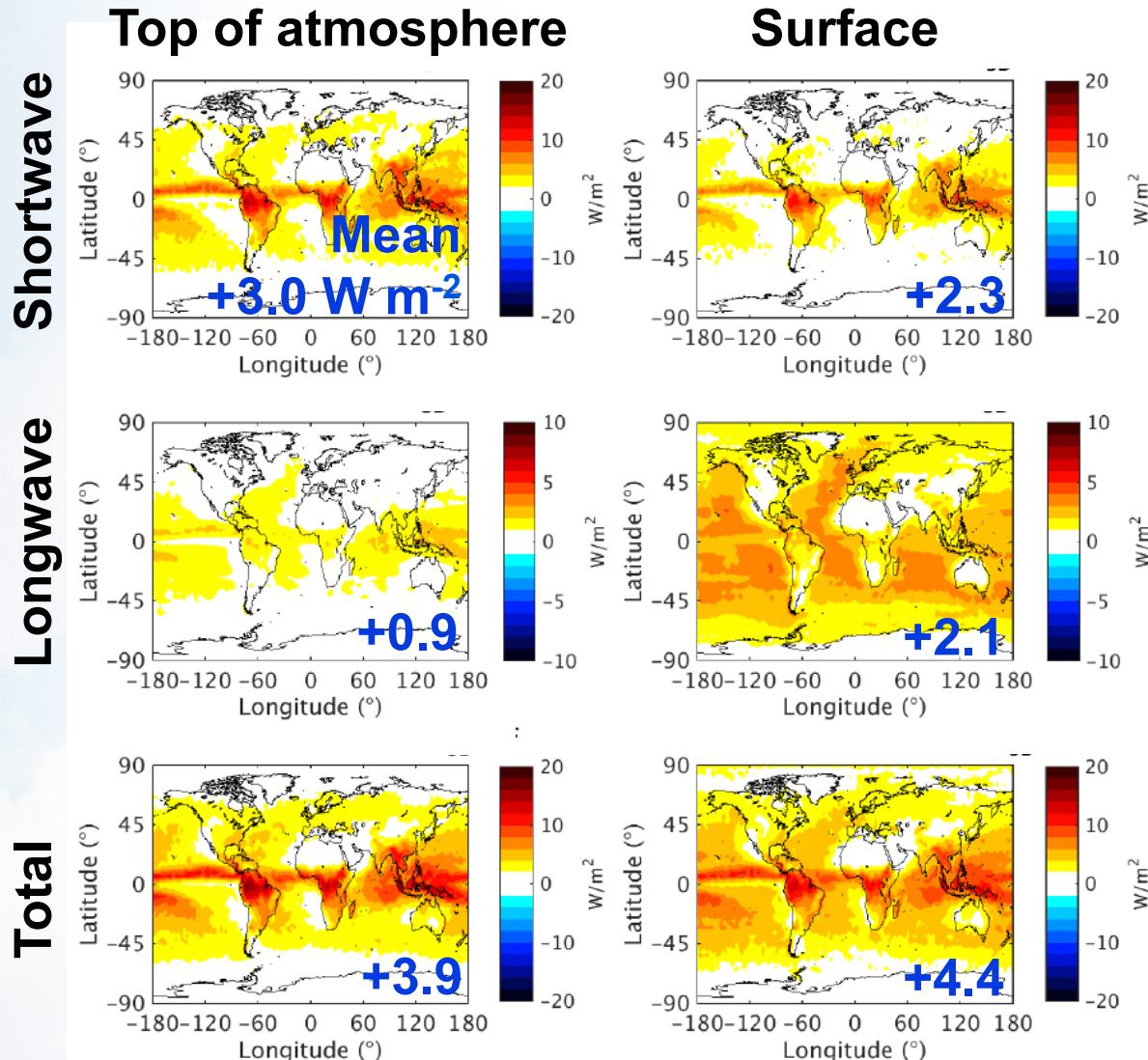
Type	Source	Res (m)	Cloud scale (km)
Cu	I3RC CRM	67	0.8±0.2
Cu	Azores radar	50	0.9±0.2
Sc	I3RC CRM	55	0.7±0.2
Sc	MODIS	1000	10±2
Ci	Stochastic model	49	4±1.5
Cb	Radar	333	14±6
Cb	CRM	250-350	5-30

- Cu & Sc: 1 km (0.7–1.4 range)
  - Approximate account for clustering
  - MODIS too coarse
- Non-BL clouds: 10 km (5–20 range)
- Obviously further refinement is needed!

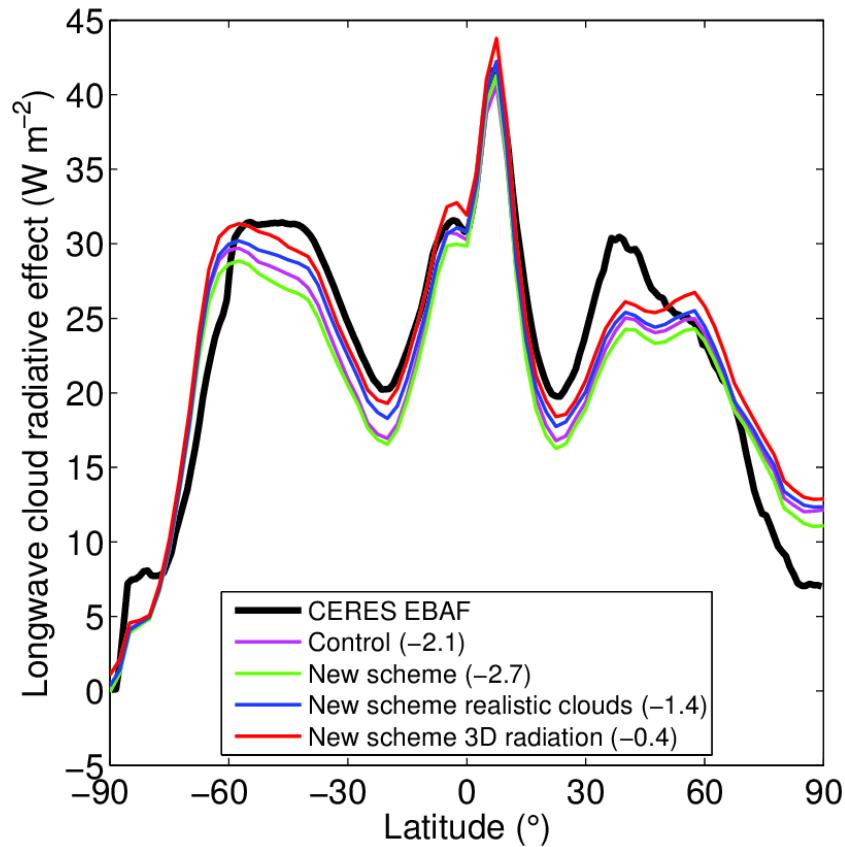
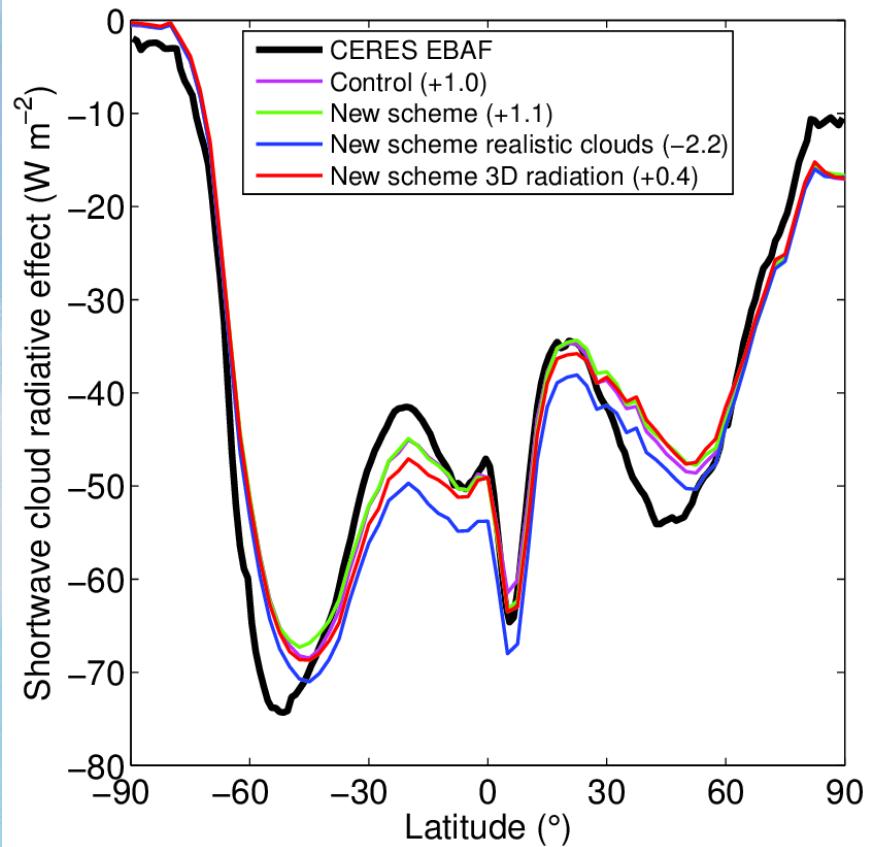
# What is the global impact of 3D radiative transfer?

- Offline calculations 1 yr of ERA-Interim clouds
- Compare McICA to SPARTACUS 3D solver (Hogan et al. 2016)
- SW & LW effects both act to warm the surface
- Similar order to effect of cloud heterogeneity or doubling CO<sub>2</sub>

*Sophia Schäfer (PhD thesis, 2016)*

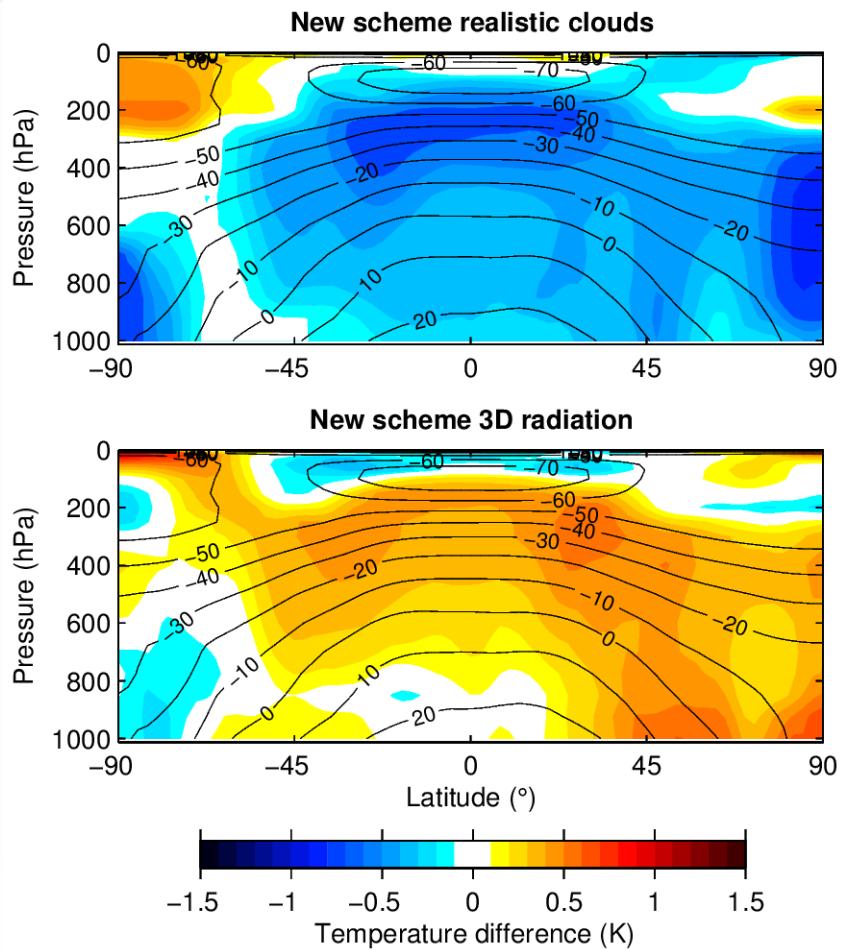
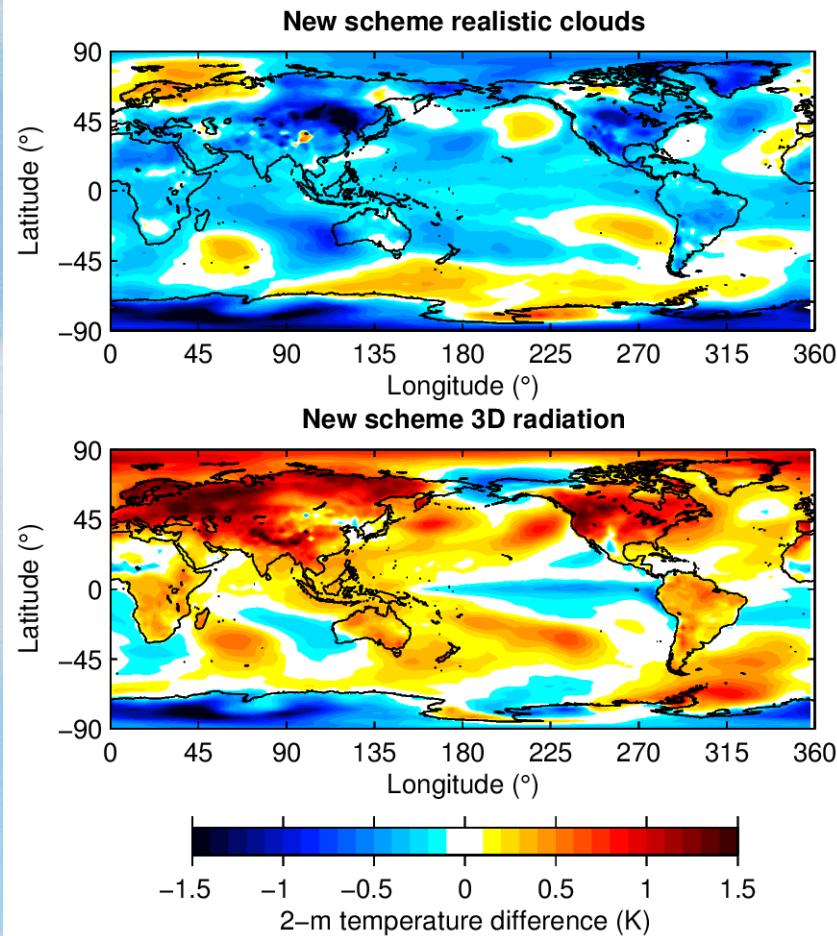


# Comparison of ECMWF model to CERES CRE



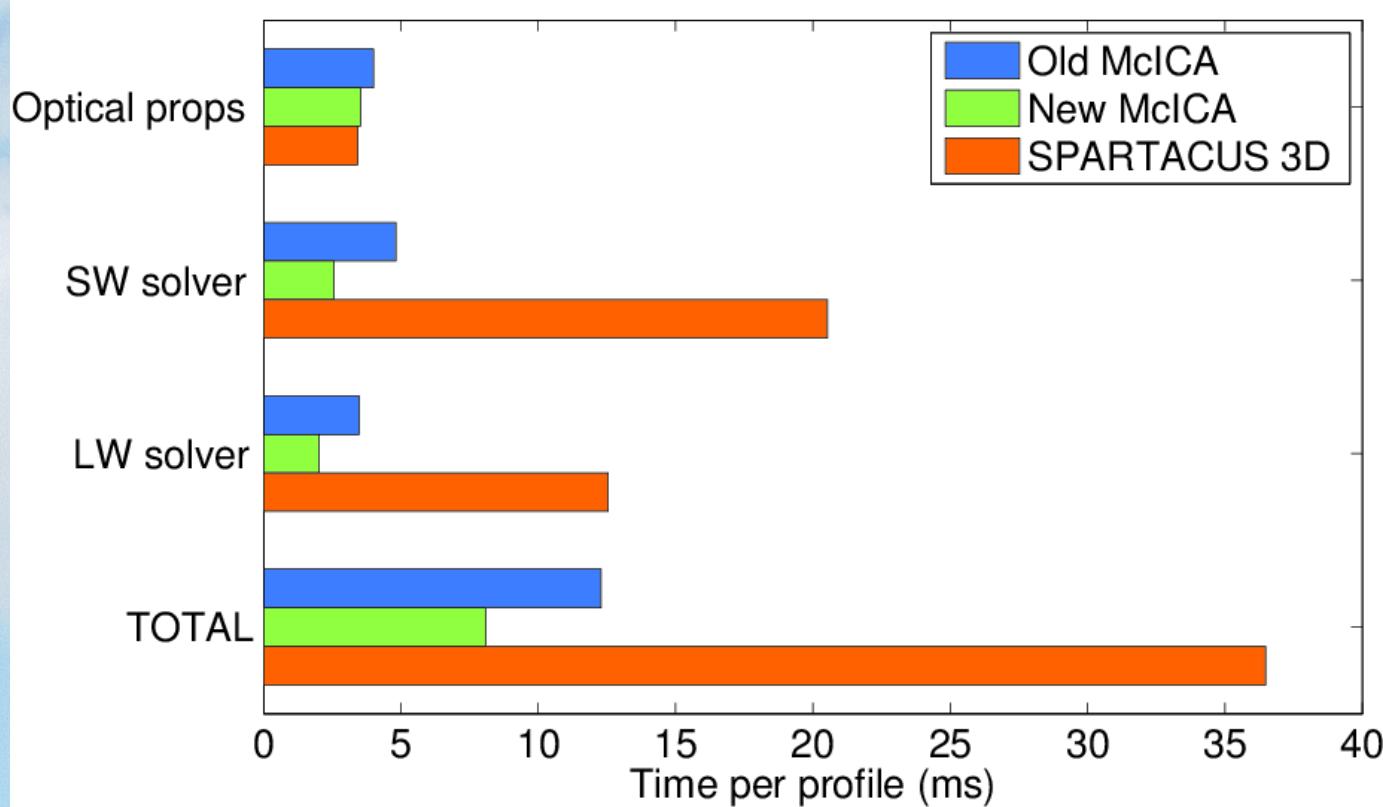
- Introduction of **3D effects** improves agreement with CERES in SW and LW
  - Is CERES longwave biased compared to model estimates (Allan and Ringer 2003)?

# Impact on temperature (8x coupled 1-yr simulations)



- Impact on 2-m temperature over land compared to ECMWF IFS control:
  - Introducing realistic cloud overlap & inhomogeneity:  $-0.3\text{ K}$
  - Introducing 3D radiation:  $+0.4\text{ K}$  (so  $+0.7\text{ K}$  due to 3D radiation) – *is this the missing physics?*

# Computational cost inside ECMWF model



- New ECRAD radiation scheme with McICA solver is 30-35% faster
- ECRAD with SPARTACUS solver: matrix exponential and other matrix operations are the main cost so further optimization needed

# Summary and outlook

- New capability to represent 3D radiative effects in a global model
- First estimates suggest  $4 \text{ W m}^{-2}$  global impact on net fluxes at surface and TOA
  - Similar to the impact of cloud inhomogeneity and overlap
  - Longwave effects are significant
  - Could help explain the cold bias in the ECMWF model? ...but many other factors need constraining too!
- Further work required:
  - More analysis of high resolution cloud observations and CRMs to characterize “effective cloud scale”
  - Comparison of SPARTACUS with full Monte Carlo calculations in a wide variety of scenes
  - Optimize SPARTACUS: perhaps treat it as a benchmark for more approximate schemes to represent 3D effects, e.g. perturbing cloud overlap (Tompkins & DiGiuseppe)
- SPARTACUS is an option in new ECMWF radiation scheme “ECRAD”
  - Offline version to be released under the OpenIFS license
- SPARTACUS idea will also be used to compute 3D effects in urban and vegetation canopies





# Do subtle radiative effects really matter for an NWP centre?

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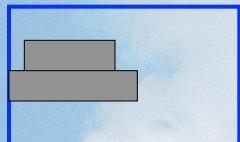
- Short to medium term
  - Surface temperature forecasts are of first-order importance
  - Solar energy industry increasingly using radiation diagnostics from NWP
- Monthly to seasonal (both coupled)
  - Predictability on this timescale from stratosphere, MJO, ocean memory – all require accurate radiation
  - Difficult to get statistical significance when evaluating different seasonal forecast systems – but a prerequisite for a skilful system is a model with a good *climate*

## Overview

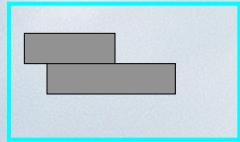
- A puzzling bias
- Representing cloud structure in radiation schemes
- Conceptual models for 3D cloud-radiation effects
- The SPARTACUS solver
- How big is a cloud?
- An estimate of the global impact of 3D radiation

# Global impact of cloud inhomogeneity and overlap

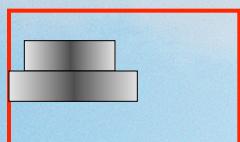
Plane-parallel,  
maximum-random



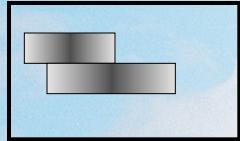
Fix only overlap



Fix only  
inhomogeneity

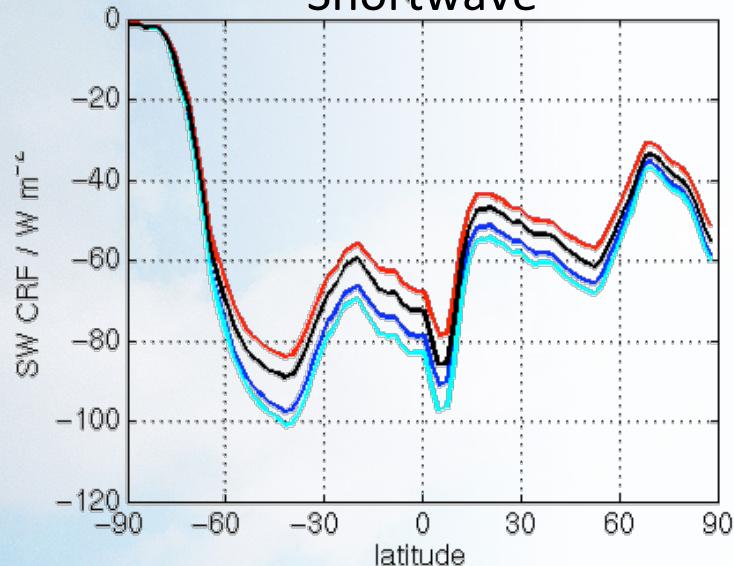


Fix overlap and  
inhomogeneity

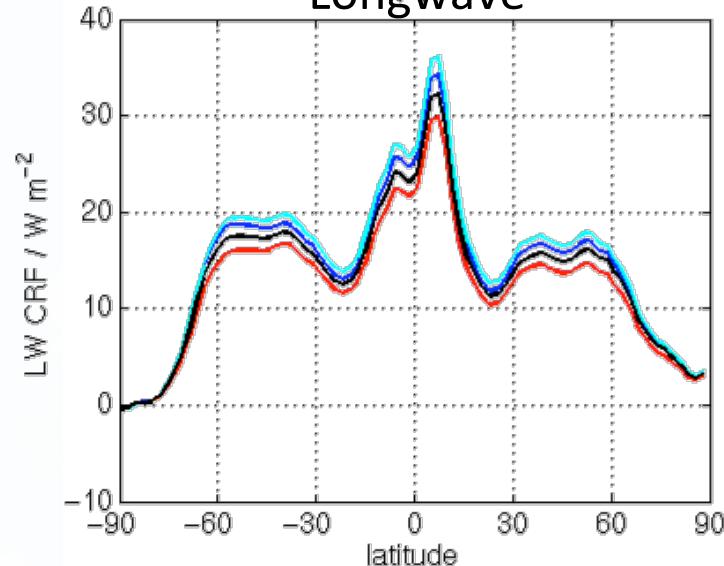


## Top-of-atmosphere cloud radiative forcing

### Shortwave



### Longwave



- Fixing just horizontal structure (blue to red) would overcompensate the error
- Fixing just overlap (blue to cyan) would increase the error
- *Need to fix both overlap and horizontal structure*

Shonk & Hogan (2010)

# Longwave equivalent

- Two-stream equations now look like this:

$$\frac{d}{dz} \begin{pmatrix} \mathbf{u} \\ \mathbf{v} \end{pmatrix} = \boldsymbol{\Gamma} \begin{pmatrix} \mathbf{u} \\ \mathbf{v} \end{pmatrix} + \begin{pmatrix} -\mathbf{b}_0 \\ \mathbf{b}_0 \end{pmatrix} + \begin{pmatrix} -\mathbf{b}' \\ \mathbf{b}' \end{pmatrix} z$$

(No solar beam and Planck function assumed to vary linearly in optical depth via inhomogeneous terms)

- Solution is a bit more complex:

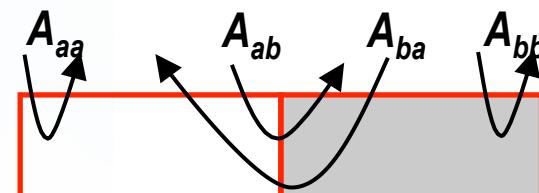
$$\begin{pmatrix} \mathbf{u} \\ \mathbf{v} \end{pmatrix}_{z=z_1} = \exp(\boldsymbol{\Gamma} z_1) \begin{pmatrix} \mathbf{u} \\ \mathbf{v} \end{pmatrix}_{z=0} + [\mathbf{I} - \exp(\boldsymbol{\Gamma} z_1)] \begin{pmatrix} \mathbf{c}_0 \\ \mathbf{d}_0 \end{pmatrix} + \begin{pmatrix} \mathbf{c}' \\ \mathbf{d}' \end{pmatrix} z_1$$

where:

$$\begin{aligned} \begin{pmatrix} \mathbf{c}' \\ \mathbf{d}' \end{pmatrix} &= -\boldsymbol{\Gamma}^{-1} \begin{pmatrix} -\mathbf{b}' \\ \mathbf{b}' \end{pmatrix}; \\ \begin{pmatrix} \mathbf{c}_0 \\ \mathbf{d}_0 \end{pmatrix} &= \boldsymbol{\Gamma}^{-1} \begin{pmatrix} \mathbf{c}' + \mathbf{b}_0 \\ \mathbf{d}' - \mathbf{b}_0 \end{pmatrix}. \end{aligned}$$

# Extension to multiple layers: the adding method

- The adding method (e.g. Lacis and Hansen 1974) can be used to combine the reflectance and transmittance matrices of pairs of layers
- In  $N$ -stream radiative transfer (e.g.  $N=16$ ), the elements of the flux vector would represent different *streams*, but the method works just as well for different *regions*
- We work up from the surface and compute the albedo of the *whole atmosphere* below each half-level
- Albedo  $\mathbf{A} = (A_{aa} \ A_{ab} \ A_{ba} \ A_{bb})$

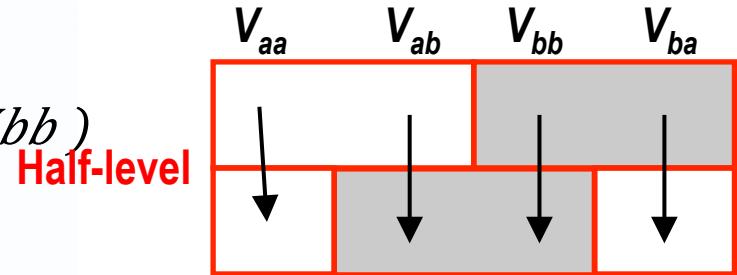


- After this we can head back down again to compute the fluxes
- For one region, this is exactly the same as solving a tridiagonal system with forward elimination followed by backsubstitution

# How do we deal with cloud overlap?

- Edwards-Slingo method: overlap matrices

- Downward overlap  $\mathbf{V} = (V_{aa} \& V_{ba} @ V_{ab} \& V_{bb})$

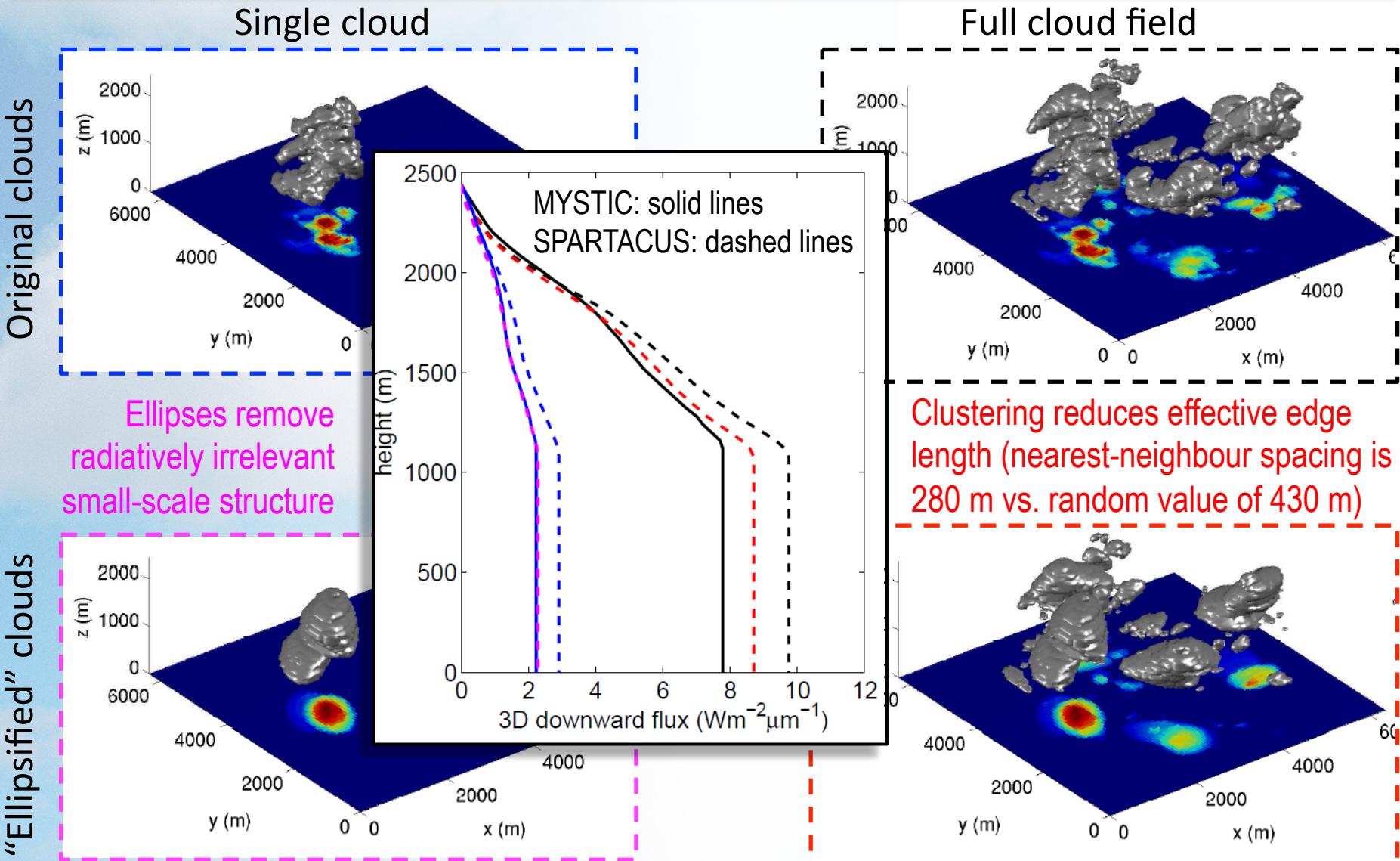


(similarly for upward overlap  $\mathbf{U}$ )

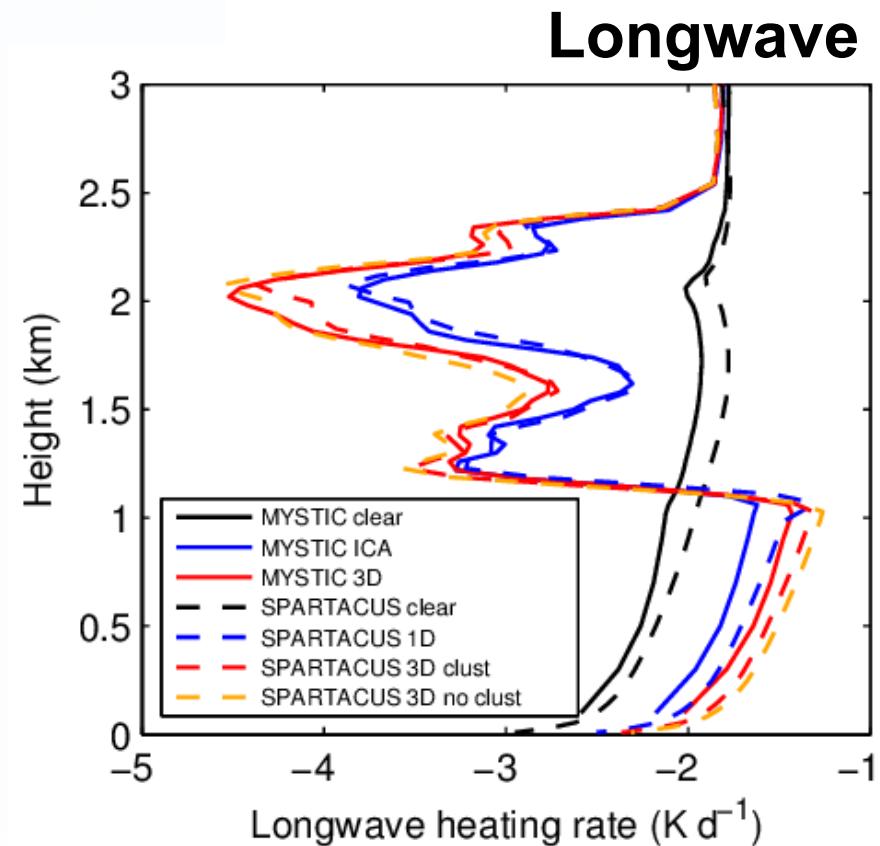
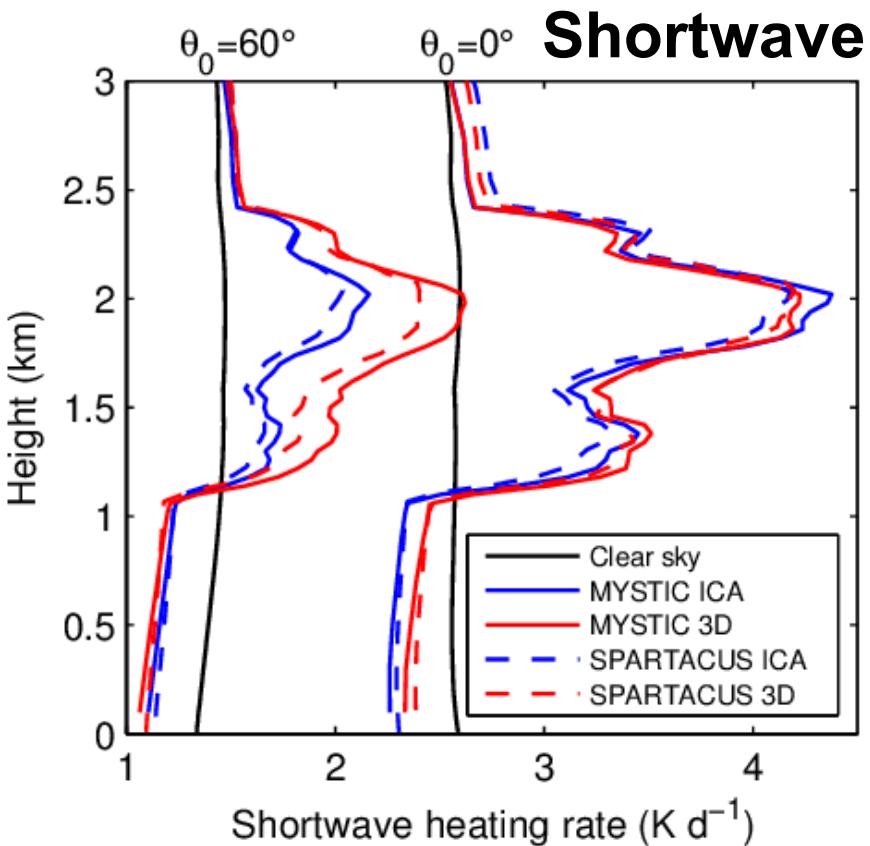
- Matrix elements calculated from a decorrelation length following Shonk et al. (2010)
- Albedo just above a half level (**A**) is related to albedo just below a half level (**B**) by  $\mathbf{A} = \mathbf{U} \mathbf{B} \mathbf{V}$

# What is LW radiatively effective cloud edge length?

Schäfer et al.  
(JGR 2016)

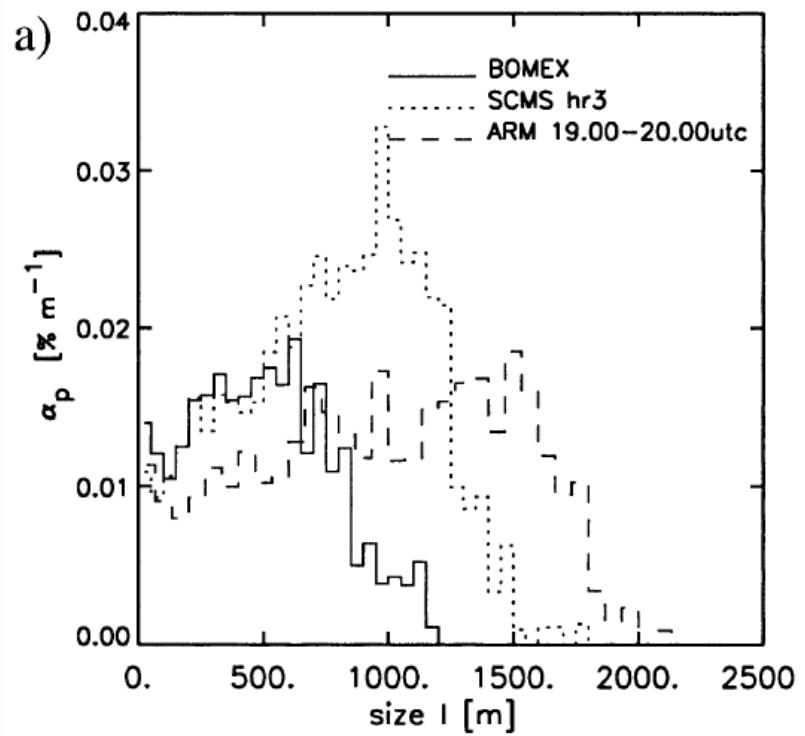
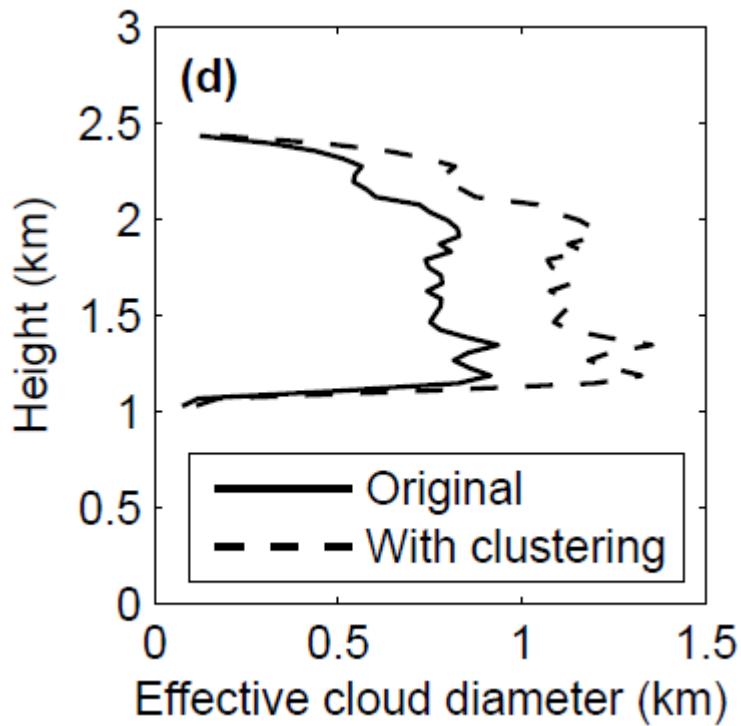


# Heating-rate comparisons with MYSTIC



- Clustering has a fairly small effect on atmospheric heating rates
- 3D effects increase longwave CRF at surface by 30% in both MYSTIC and SPARTACUS (42% in SPARTACUS if clustering effect not represented)

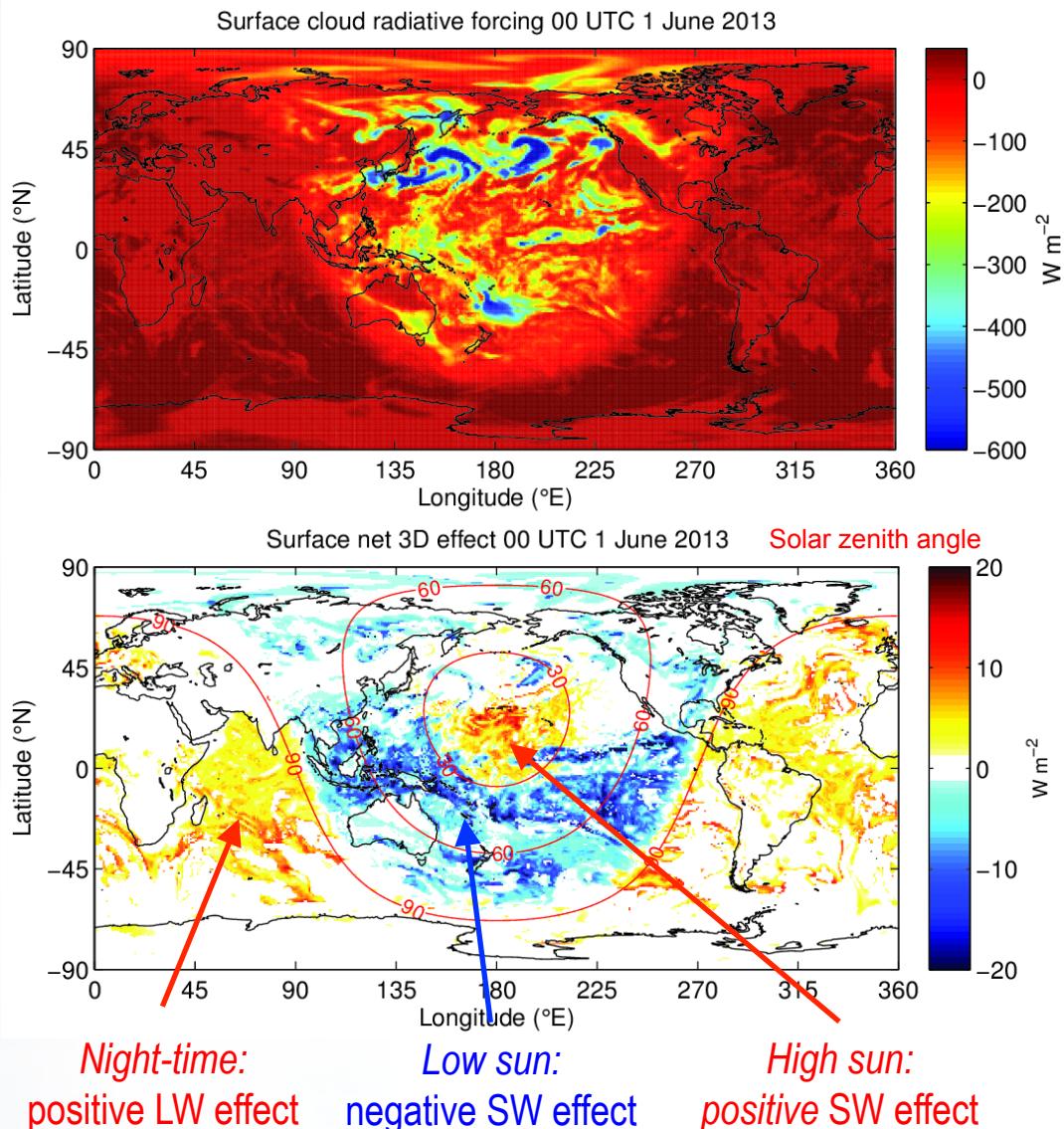
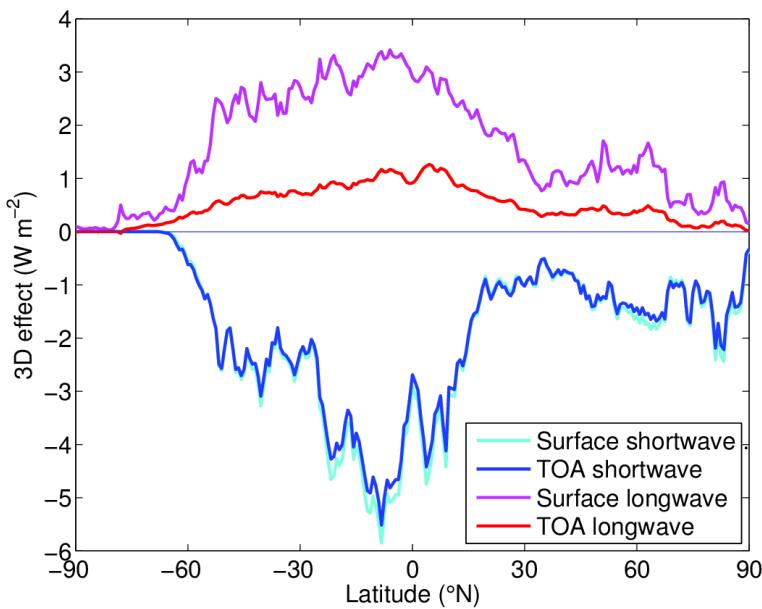
# What is the effective size of typical cumulus clouds?



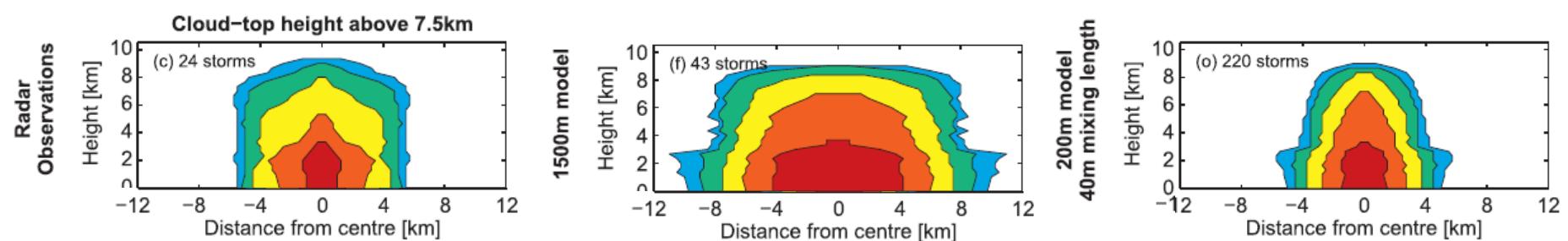
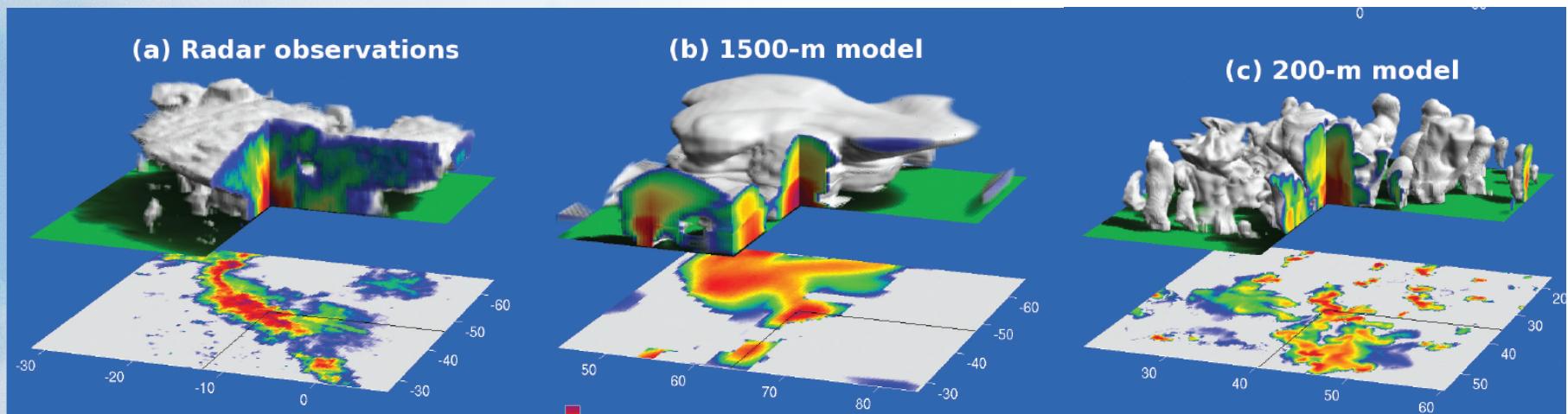
- This study: between 0.5 and 1 km
- Neggers et al. (2003): cloud resolving model applied to a range of cumulus experiments

# Towards a global estimate of the impact of 3D effects

- Instantaneous cloud radiative forcing applying SPARTACUS to one ERA-Interim clouds
- To get cloud edge length, assume cumulus horizontal length scale is 750-m, all other clouds 10 km



# Effective size of deep convection (Stein et al., BAMS 2015)



- Radar observations suggest cores of UK storms around 10 km wide
- Don't trust size of storms in models with grid spacing larger than around 1 km (Met Office model in this case)